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Muon radiography of volcanoes and the challenge at Mt. Vesuvius

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1. Introduction

Muon radiography is based on the observation of the absorption of muons in matter, as the ordinary radiography does by using X-rays. The interaction of cosmic rays with the atmosphere provides an abundant source of muons, which can be used for various applications of muon radiography and in particular to study the internal structure of the edifice of volcanoes.

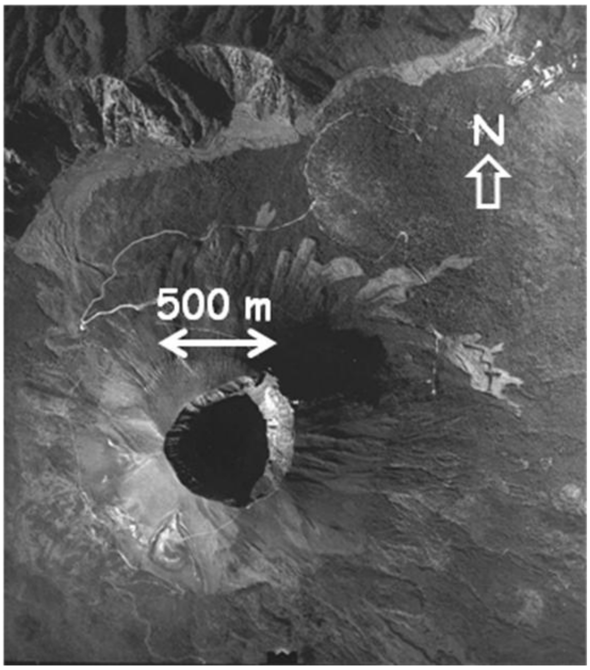

Fig. 1. Aerial view of Mt. Vesuvius; in the upper side part of Mt. Somma is visible.

Muon radiography was first proposed to determine the thickness of snow layers on a mountain [1]. The first application was realised in 1971 with the seminal work of Alvarez and collaborators for the search of unknown burial cavities in the Chephren's pyramid [2]. The pioneering work done in Japan for the radiography of the edifice of volcanoes by using quasi-horizontal cosmic ray muons [3-11] has opened new possibilities for the study of their internal structure. The resolution which can be achieved is of the order of 10 m, which is difficult to be addressed with other techniques. The status of the art has been reviewed in a recent workshop [12].

The field of muon radiography is rich of perspectives for other applications: the study of Maya pyramids [13-14], investigations of the status of iron furnaces [15], radiography of mechanical structures using muon beams [16] and others [17-23] among which security related applications.

The present project concerns the possibility to apply muon radiography to study the edifice of a volcano at very high risk, Mt. Vesuvius and, in doing that, to develop instruments and methods suitable for later utilization in other volcanoes.

Mt. Vesuvius is a cone, 1280 m high above the sea level, which has grown within the ancient caldera of Mt. Somma (Figs. 1 and 2). Mt. Somma was formed about 19,000 years ago and its original height has been estimated to about 2000 m. Only the northern ridge of the Mt. Somma caldera is actually left as a part of the ancient structure, whose collapse started during two large eruptions occurring about 18,000 and 16,000 years ago. The history of the volcano has been characterized by dramatic plinian and sub-plinian eruptions, the most famous of which caused the destruction of the towns of Pompeii, Herculaneum and Stabiae in AD 79 as reported by Pliny the Younger [24]. In relatively recent times several eruptions have occurred and the most recent one occurred in 1944. The eruptions have dramatically altered the morphology of the mountain, from what can be supposed to have been before the AD 79 eruption (Fig. 3) to the present morphology. An impressive picture of the evolution in the course of the years 1630-1944 is given in Ref. [25]. At present the monitoring system does not reveal signs of notable activity. For the past, a correlation has been observed between the time from the last eruption and the strength of the eruption itself. The present apparent quiescence raises questions on a possible storing of energy which could be delivered in a future eruption.

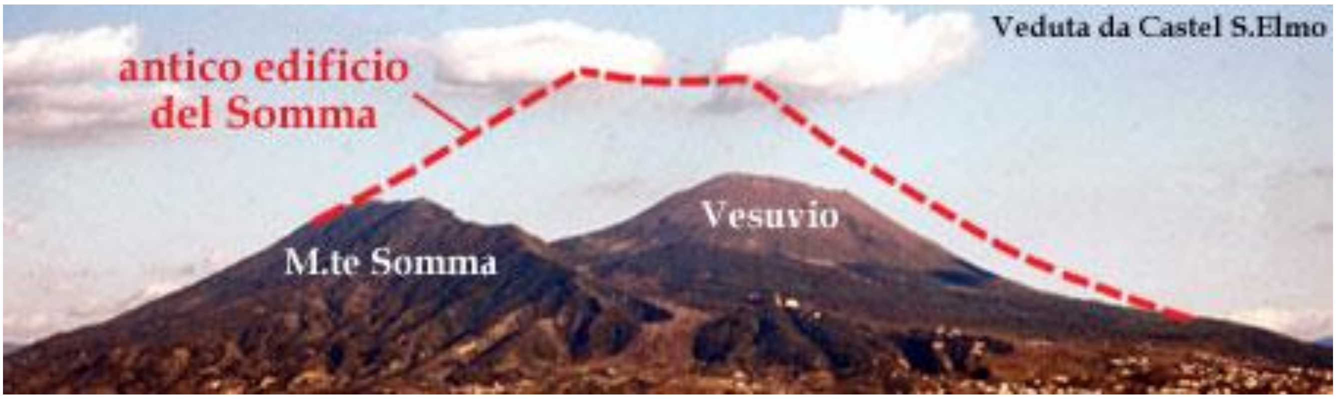

Fig. 2. Mt. Vesuvius in the caldera of Mt. Somma, as seen from Naples.

Fig. 3. Dionysus and Mt. Somma (presumably) before the AD 79 eruption ***(fresco from Casa del Centenario, Pompei; now at Naples Archaeological Museum)***

The population living at the base and along the slopes of the volcano, in a “red” area which has been classified at the highest volcanic risk in Europe, reaches about 600,000 people [25]. The knowledge of the inner structure of the volcano edifice and subsoil structure is therefore of the greatest importance, to build realistic scenarios of the next eruption through accurate simulations of the magma upraising mechanism and eruption.

Mt. Vesuvius is among the most studied volcanoes in the world. The volcano has been thoroughly investigated using geophysical methods. The Vesuvian Observatory was set up in 1841, in times when it was essential for volcanologists to stay close to volcanoes. It is the oldest volcano observatory in the world. Its ancient building was constructed on the volcano slopes at about 600 m a.s.l.. The main research activities of the Vesuvian Observatory, which is now also in charge of monitoring Stromboli, have been moved to the headquarters in Naples. The historically pioneering research infrastructure at Mt. Vesuvius is still operational by hosting monitoring instruments and a scientific museum.

We outline and propose here a project (MU-RAY [1]) to study Mt. Vesuvius by muon radiography. The task is very challenging, due to the morphology of the mountain and to the aim of investigating deeper structures than in previous applications of muon radiography to volcanoes [3-11].

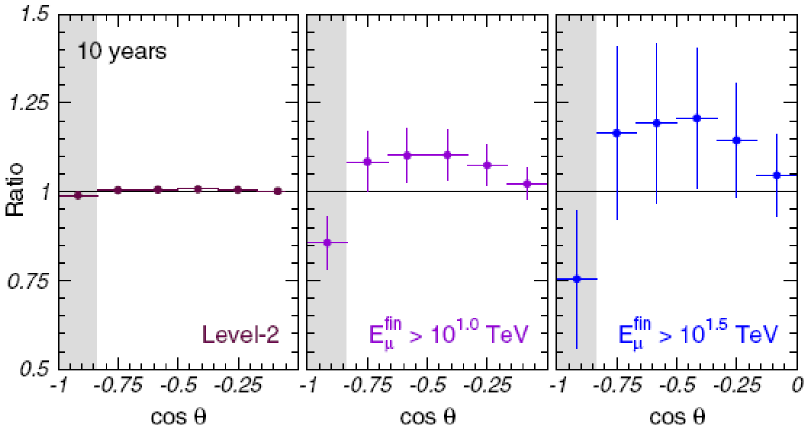

Fig. 4. Ratio of zenith angle distribution of expected events over those from a homogeneous Earth matter distribution for different values of the energy threshold of the events. The error bars show the expected statistical errors in 10 years of IceCube operation[29].

To investigate the internal structures of volcano edifices at greater depths below their summit, where absorption strongly reduces the muon flux, detectors of area larger than so far used are needed though maintaining features of portability in a volcanic environment. Detectors of larger area reduce the time required for a radiography and, in application at shallower depth, may aim to the (quasi) real time response required for monitoring purposes. The realisation of a large area detector for the study of Mt. Vesuvius, exploiting new technologies developed for Particle Physics, would have a broader interest in view of its utilization for the study of other volcanoes. We thus plan to operate in the framework of a scientific network sharing our objectives.

2. The framework of Geoparticle Physics

The exploration of the internal geological structure of the Earth by using elementary particles is what can be now denoted as Geoparticle Physics. The idea is quite old, but only in recent times it has entered in a phase of first production of quantitative estimates and data, with a general renewed vitality which makes these times very attractive. This new discipline can be split in two main research fields essentially defined by the source of the probe: cosmic radiation at high energy (as in the present proposal) or low energy neutrinos produced by radioactive decays inside the Earth.

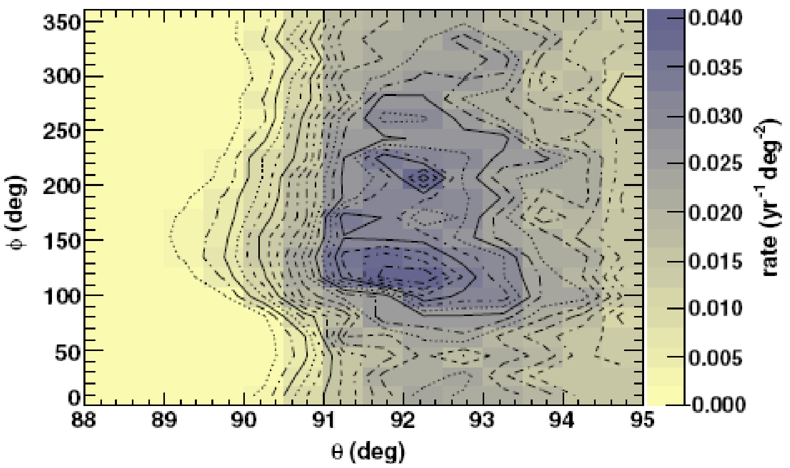

Fig. 5. Event rate as a function of azimuth and zenith for the active Auger volume, in the case of Earth-skimming ν_τ showers ($85^0<\theta<95^0$) assuming E^{thr} = *O* (EeV) for the τ [32].

[1] MUon RAdiographY

2.1 Cosmic radiation and Geoparticle Physics

In probing the structure of the Earth by means of the cosmic radiation we can talk in terms of two fields defined by the particle probe chosen, namely muons produced by cosmic rays in their interaction with the atmosphere and cosmic neutrinos. It is worth stressing that these two research fields, both connected to astroparticle physics, share similar methodologies and are therefore culturally and practically related. In both cases the charged leptons, either muons or tau leptons, are the relevant particles for the observation. The Monte Carlo required to study the detector performance in relation with its features is essentially the same for both fields, with in the case of neutrinos an additional modulus able to deal with neutrino (charged or neutral current) interactions.

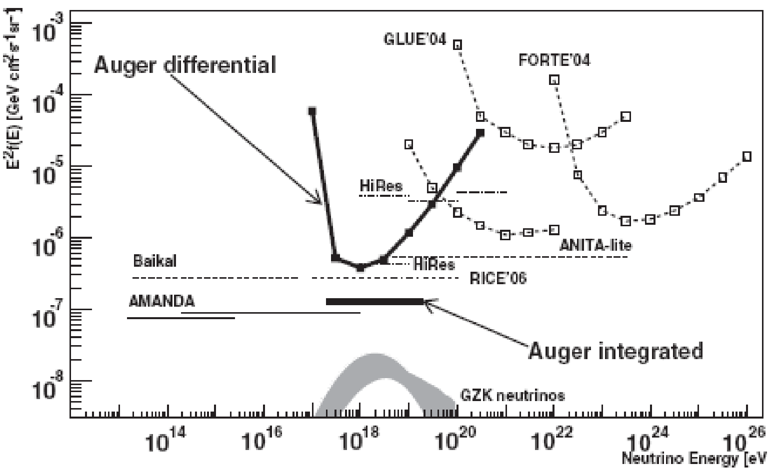

Fig. 6. Limits at 90% C.L. for a diffuse flux of ν_τ from the Pierre Auger Observatory [35]

We will devote the main part of this section to the (more advanced) issue of muon radiography of geological structures, which is the topic addressed by the present project. Nevertheless, for what said above, we outline the very interesting opportunity offered by neutrino radiography which will become a reality with the construction of giant Neutrino Telescopes, as IceCube under the Antarctic ice [26] or the KM3 telescope under the Mediterranean sea [27]. We will also illustrate the observations at the Pierre Auger Observatory [28].

2.1.1.Geoparticle Physics with cosmic neutrinos

Due to the extremely large interaction length, which is of the order of the Earth's radius for neutrinos with a few TeV energy, neutrinos represent a unique probe of the Earth's density profile. They are capable to explore the Earth's core, mantle and their boundary (Core Mantle Boundary, in brief CMB) which determine its geo-dynamo as well as the feeding mechanism of hotspots at the surface. The present knowledge of the CMB is derived from body-wave and free-oscillation studies. The information, while more precise than what we can realistically expect from neutrino radiography in the foreseeable future, cannot reduce ambiguities in our present model of the CMB associated with the fact that arrays of seismometers only provide regional information, and that free-oscillation data only reveal one dimensional structures. The trade-off among density, temperature, and chemical structure for body-wave studies increases the uncertainty of the value for the

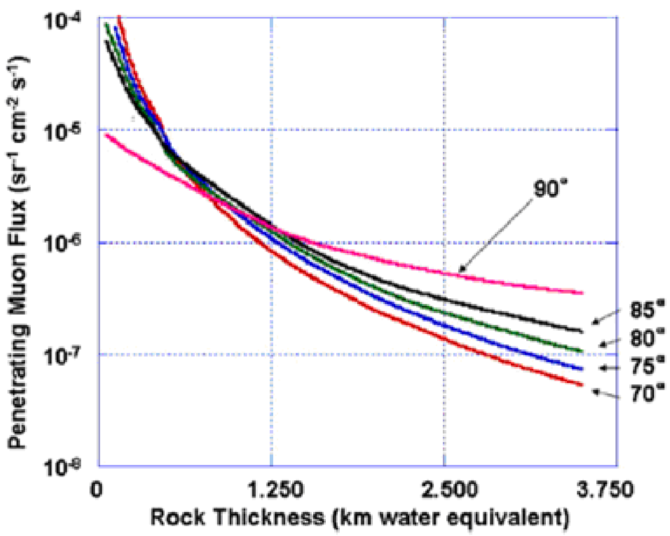

Fig.7. Integrated flux of cosmic ray muons at various zenith angles penetrating through a given thickness of rock [7].

density. For these reasons, aspects of the global structure of the CMB region require confirmation. A study done for IceCube indicates (see Fig. 4) that neutrino telescopes under construction or presently foreseen have to be operated for 10 years to locate the CMB [29]. However, they will allow to establish the average core and mantle density as a function of longitude, thus providing the first independent global survey of the CMB region.

The presence of matter surrounding a giant apparatus for the study of very high energy cosmic rays can represent an opportunity to enhance its detection performance. A chain of mountains, like the Andes for the Pierre Auger Observatory [28,30-32], or the Sicily coast line for the NEMO neutrino telescope of KM3NeT [27,33,34], are the target for cosmic tau neutrinos which generate charged leptons and can be consequently detected. The enhancement of tau neutrino detection performance due to Earth-skimming processes [32], which is observed as a positive shadow of the Earth's crust nearby the Observatory (see Fig. 5), has allowed the Auger collaboration to set an upper bound on ultra high energy cosmic neutrinos (see Fig.6) [35].

2.1.2. Geoparticle Physics with cosmic ray muons

Differently from neutrinos, muons generated by the interaction of cosmic rays in the atmosphere (the so-called atmospheric muons) can only cross a few km of rock at most, and thus they can probe superficial structures only. The internal structure of the Earth's crust is currently studied by seismological, electromagnetic or gravitational geophysical observations. However, these measurements are rather indirect and have substantial intrinsic uncertainties. Therefore it is desirable to find independent ways to assess the subsurface structure. Among the measured properties of the Earth's interior, density plays a special role because it is most readily interpreted in terms of composition and state. The muon radiography thus represents a very interesting tool even though the main problem to overcome is related to the small expected flux of atmospheric muons for large values of thickness of rock crossed by them (Fig. 7). To achieve an interesting sensitivity in a practical time thus one needs to determine the required detector area in relation to the thickness of the geological structure to be studied and to ensure its feasibility.

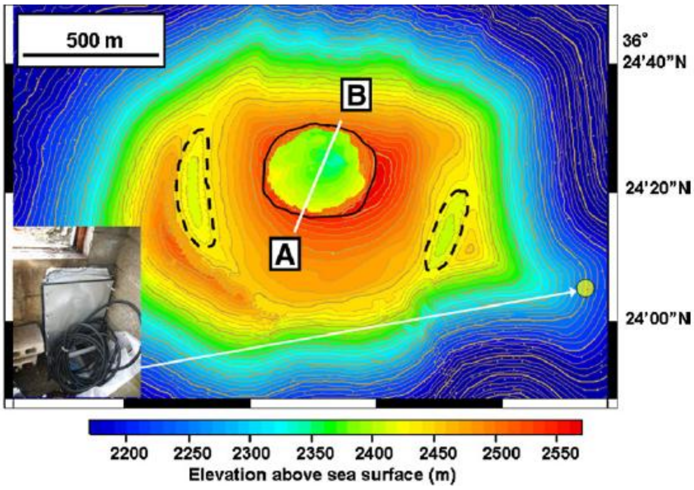

Fig. 8. Map of Mt. Asama with the location of the cosmic ray muon detector indicated by an arrow. The line A-B shows the vertical cross-sectional plane as seen by the detector [7].

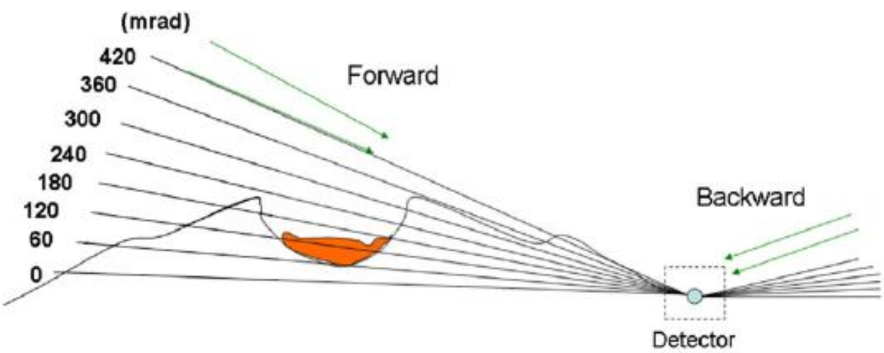

Fig.9. Cross section of Mt. Asama showing geometrical arrangements used in the measurement [7].

Absolute density measurements using vertical cosmic ray muons have been reported in 1987 [36,37] and by the MACRO experiment in the underground Gran Sasso Laboratory [38].

The observations performed by H.K.M. Tanaka and collaborators [4-11] have been a breakthrough for muon radiography and have clearly shown the potentialities of this technique. For the work reported in Ref. [7], a muon detector with an area of 0.4 m^2 was located at about 1 km from the summit crater of Mt. Asama in Japan, as shown in Fig. 8. The muon tracks reconstructed by the detector were analyzed to determine the absorption along different ray paths through the summit crater region (Fig. 9) and consequently to map the density. The authors have radiographically imaged the rock below the bottom of the crater of Mt. Asama and have detected a dense region, which corresponds to the position and shape of a lava mound created during the last eruption (Fig. 10).

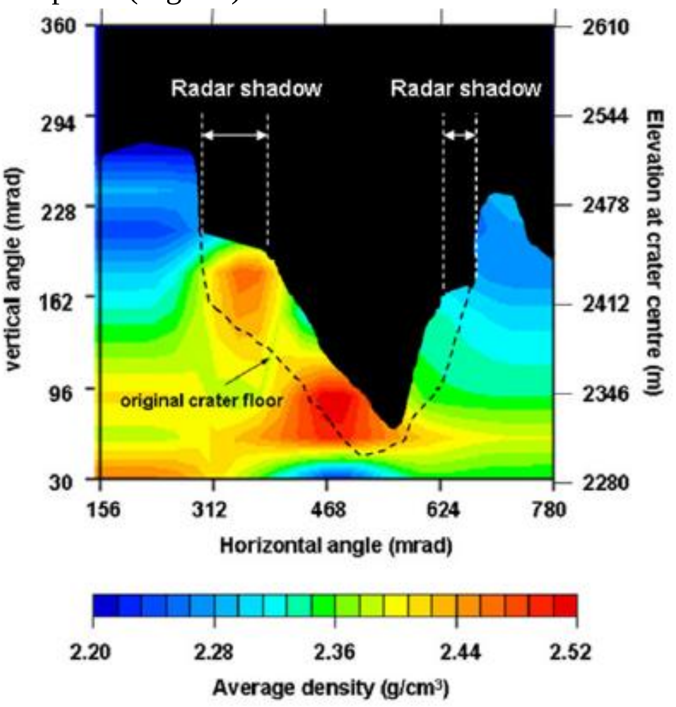

Fig. 10. Reconstructed average density distribution of the summit of Mt. Asama [7].

An angular resolution of the muon detector of 10 milliradians (mrad) corresponds to a spatial resolution of 10 m at a distance of 1 km. The measurements are suitable for studying the shallow structure of the crust at sites where it cannot be well resolved by conventional electromagnetic or seismic techniques because of the strong structural heterogeneity.

The method can provide three dimensional images of internal structures by making measurements from two or more different points of observation.

2.2. Geoparticle Physics with neutrinos from the interior of the Earth

Although methodologically disconnected from the proposed research, for completeness we briefly outline the investigations of the interior of the Earth by low energy neutrinos from the decays of radioactive elements, referring to dedicated literature [39,40] for more detailed information. The decay of radioactive elements in the Earth is an important source of geothermal heat. The measurement of the arrival directions of neutrinos generated in these decays, can thus give a three-dimensional picture of the Earth's composition and shell structure, as well as tell how much heat is continuously produced by radioactive decays and how much is a primordial leftover from the birth of the Earth. The mapping of the Earth's interior might also help to understand what powers the magnetic field of the Earth and what dominates the geodynamo.

The experiments designed to detect low energy neutrinos and investigate the neutrino mass by observing the so called neutrino oscillations have the opportunity of detecting geoneutrinos. The KamLAND experiment [41], primarily designed to detect anti-neutrinos from nuclear reactors, reported 9 events due to geoneutrinos [42]. This first detection of geoneutrinos already demonstrates that radioactivity is an important source of new heat for the Earth and the future is promising. The Borexino experiment [43] has been designed for solar neutrinos and has among its aims the observation of geoneutrinos [43,44]. The SNO Collaboration [45] has been thinking of using a scintillator with gadolinium in its detector designed for solar neutrinos.

3. The motivation for volcanology and for the study of Mt. Vesuvius

Mt. Vesuvius is a stratovolcano located in Southern Italy within a graben (Campania Plain) formed in the Plio-Pleistocene. It is the southernmost and the youngest of a group of Pleistocene volcanoes, three of which (Mt. Epomeo in Ischia Island, Phlegrean Fields and Mt. Vesuvius) have erupted in historical times. Mt. Vesuvius is located 15 km east of the city of Naples. Its morphology is characterized by a volcanic cone (called Gran Cono), which reaches 1280 m a.s.l. and it is built within the caldera of Mt. Somma. The AD 79 eruption destroyed Pompeii, Herculaneum and Stabiae. It is the first catastrophic eruption described in considerable details [24].

The chronology of Mt. Vesuvius eruptions shows that at least seven violent Plinian as well as numerous sub-Plinian eruptions occurred, many of which were separated by long periods of quiescence. The chronology suggests also that the longer is the quiescence period the more violent is the renewal of activity. The last period of persistent volcanism of Mt. Vesuvius started after the 1631 Plinian eruption and lasted till 1944. Since that time Mt. Vesuvius has been quiescent and actually only a moderate seismicity and fumaroles testify its activity.

The volcanic activity of Mt.Vesuvius is monitored by a multi-parametric observation system for the continuous recording of seismicity, ground deformation and gas emission data that are transmitted to the operating centre of Vesuvian Observatory, located downtown in Naples.

The volcano has been the object, in recent years, of accurate geophysical and volcanological studies. In particular, active/passive seismic tomography and wave reflection studies have been performed with the aim of improving the knowledge of the deep geological structures beneath the volcano. The structural model of the volcano is essential to assess realistic scenarios of the eruptive activity and it is the basis for the identification of possible precursors of future eruptions. Several important results have been obtained by previous seismic studies:

- the presence of a high-velocity body located 1-1.5 km underneath the summit caldera of the volcano and interpreted as an array of magmatic dykes solidified at small depth [46];
- no evidence for the occurrence of a reservoir shallower than 8 km [47];
- the 3-D reconstruction of limestone top morphology [48];
- the evidence for an extended (at least 400 km^2) low-velocity layer at about 8 km depth interpreted as a sill with partially melted magma interspersed in a solid matrix [47];
- the whole volcanic area is characterized by high Vp/Vs ratio (1.9) which is an indicator for high fluid percolation [49];
- the seismicity is concentrated in the upper 2-3 km of the limestone layer [49,50].

The resolution of seismic and more generally of geophysical techniques (seismological, electromagnetic, gravitational) is rather low, being able to define space variations of elastic properties with an accuracy of several hundreds of meters in the optimal acquisition conditions. This insufficient resolution does not allow to characterize small volcanic structures (conduits, high density anomalies, magma intrusions) that can have an important role in forecasting time and magnitude of hazardous future eruptions.

The cosmic ray muon radiography is a technique for imaging the variations of density inside a hundreds of meters volcanic cone. With resolutions up to tens of meters in optimal detection conditions, muon radiography can give us images of the top region of a volcano edifice with a resolution that is significantly better than the one typically achieved with conventional gravity methods and in this way can give us information on anomalies in the density distribution, such as expected from dense lava conduits, low density magma supply paths or the compression with depth of the overlying soil.

The combined use of different techniques as muon radiography, seismological and gravity measurements can provide a wide vision of the shallow/deep internal volcanic structure including also the topmost part of the volcano edifice that is important to monitor the state of the volcano and provide useful data to predict the evolution of an eruption. Moreover, by using the muon radiography technique one can obtain a density image of the investigated area. In addition the availability of accurate rock density measurements by muon radiography allows to infer about the chemical composition and thermal state of the volcano crater.

The feasibility of periodically repeated cosmic ray muon radiographies opens also new perspectives for the near-real time investigation of volume/deformation space-time changes (monitoring in the four space-time dimensions) of the volcanic edifice structure, induced by inner processes of mass re-distribution. The occurrence of inflation episodes due to the magma up-rising or hydro-thermal fluid circulation can be the cause for significant volume and rock physical property changes which can produce density variations detectable by cosmic ray muon radiography. This would have great relevance for the monitoring of volcanic hazard and quantitative assessment of volcanic risk.

The muon detector system that we propose to develop could be useful to investigate the internal structure of other volcanic edifices than Mt.Vesuvius. The persistent eruptive activity and edifice morphology make the "Strombolian" volcanoes the ideal laboratories for application of muon radiography techniques, as for instance, the Stromboli volcano in Aeolian Islands in southern Italy. Stromboli is considered one of the most active volcanoes in the world, and its persistent but moderate explosive activity is only interrupted by rare episodes of more vigorous activity accompanied by lava flows. This volcano is particularly suited for the application of muon radiography technique, since it is an open conduit volcano characterized by persistent conduit degassing and explosive dynamics. A detailed image of the volcanic edifice can help to map the conduit network path and monitor the eruption processes by surveying the magma emplacement at shallow depths close to the vents [51]. Stromboli is a composite stratovolcano that steeply reaching ~900 m above sea level, allows to image a large portion of the volcano edifice by muon radiography.

The activity at Stromboli is characterized by very shallow seismicity (occurring at about 200 m depth below the cone [52] associated with eruptions as well as the continuous volcanic tremor and explosions that are concentrated at depths shallower than 200 m beneath the summit crater [53]. For these reasons the muon radiography at Stromboli can provide with detailed information of the shallow part of the volcano giving useful insights of the shallow magma conduit shapes and geometries that are essential to understand the activity and dynamics of the volcano and then for estimating its hazard and critical levels.

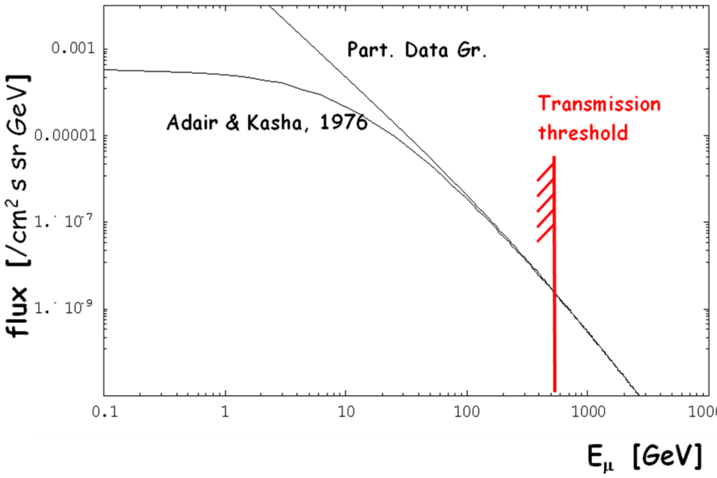

Fig. 11. The expected muon flux at the sea level for an arrival direction at 70^0 with respect to the vertical.

Actually the Stromboli volcano is continuously monitored by a multi-parametric geophysical system (seismic, infrasound, thermal infrared, ground deformation, chemical composition of fumaroles). The comparison and the combined use of all this data with the information obtained by muon radiography will be integrated into a unique three-dimensional structural model of the volcano.

The application of the muon radiography to a large volcano like Mt. Etna should also be studied.

4. Estimate of muon rates and simulation of the experimental apparatus

A full Monte Carlo simulation is in progress and will be outlined later on in this section. Let us first sketch a simple model calculation which allows to estimate the muon flux and thus understand the order of magnitude of the area which is needed for the muon detector.

For energies larger than 100 GeV, the atmospheric muon flux at the top of the atmosphere is described by the following expression [54]

$$\frac{dN}{dS\,dt\,dE\,d\Omega} = 0.15E^{-2.7}\left[\frac{0.9}{1+\frac{1}{92}E\cos\theta} + \frac{0.1}{1+\frac{1}{540}E\cos\theta}\right]\left(cm^2\ s\ GeV\ sr\right)^{-1}$$

where θ denotes the zenith angle (measured from the vertical) and E is measured in GeV. The muon flux falls steeply with energy, with a power index -2.7. This makes increasingly difficult observations requiring the traversal of large thicknesses of rock, as already pointed out in relation

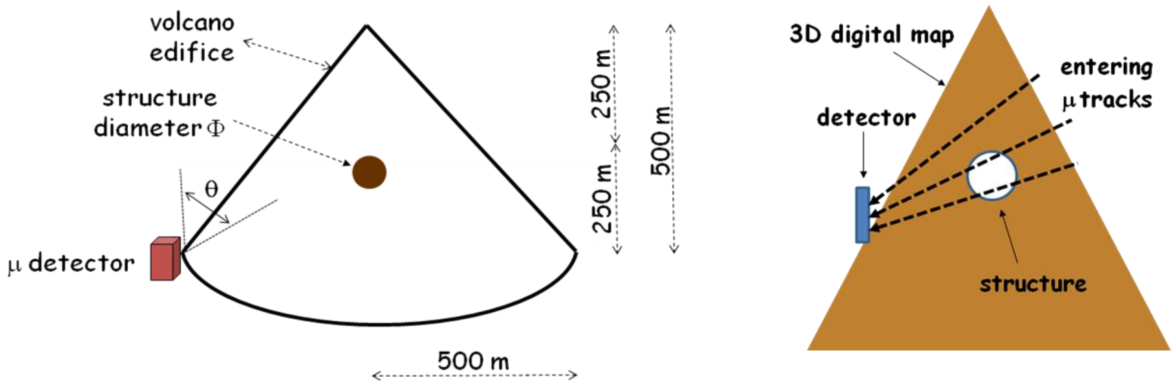

Fig. 12. Simplified model for the mountain-detector system, with an internal structure to be studied.

to Fig. 7. To set the energy scale of interest for muon radiography of volcanoes, let's consider that the energy loss of relativistic particles in matter is approximately 2.5 MeV g^{-1} cm^2 [55]. With a density of 2.2 g cm^{-3}, it results in a loss of about 0.5 TeV km^{-1}.

By taking into account the energy loss in the atmosphere, the curvature of the Earth and the possible decay of muons travelling towards the surface, one gets a new expression, which we plot in Fig 11 for $\theta = 70^0$ and represents the expected muon flux at the sea level for a given arrival direction angle. Two parameterizations [54,55] are compared in Fig 11, which also indicates the transmission threshold in the traversal of about 1 km of rock. One sees that the two parameterizations agree in the energy region which is relevant for our application. The parameterization given in Ref. [54] has been used in Ref. [7] and related papers.

Φ of structure [m]	20 ρ = 0	50 Δρ/ρ_0 = 0.1
Rate N through structure [m^{-2} day^{-1}] (ρ_0 = 2.2 g cm^{-3}, E_μ > 0.5 GeV)	2.5	16
ΔN/N by structure	0.09	0.02
Events for 3 σ detection of structure	1,150	20,000
Detector area x time [m^2 month]	15	40

visible

Table 1. The product of detector area times measurement time required to see substructures, according to the simplified model of Fig. 12.

In order to obtain a preliminary estimate of the product detector area x exposure time needed for the muon detector, let us consider the geometrical model shown in Fig. 12. In the model, we consider the presence of an internal structure with diameter Φ.

By taking into account the energy loss of muons in rock and their survival probability, we obtain the results shown in Table 1, which gives the flux muons with energy larger than 0.5 GeV entering detector and detector area x exposure time required in order to reveal an internal structure (at 3σ level), in two different cases: an empty cavity of 20 m diameter and a structure of 50 m diameter characterized by a 10% different density.

The model calculations reported above indicate that detector areas of 10 m^2 or more are required. A full simulation is needed to evaluate the sensitivity which can be expected. This full simulation is in progress. It will be performed using GEANT4 (Geometry ANd Tracking) [56].

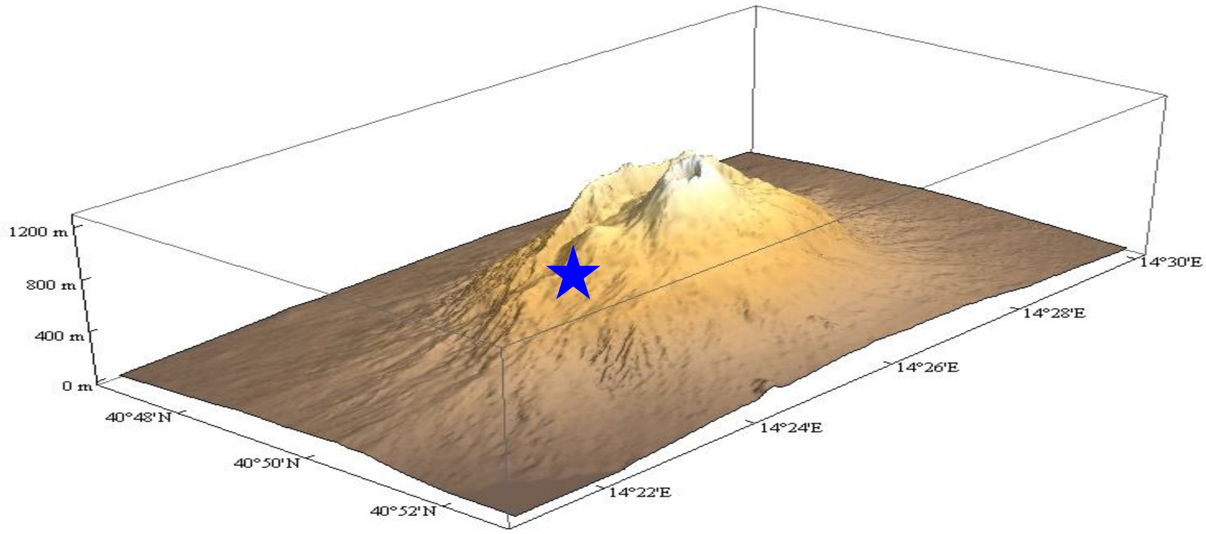

Fig. 13. The 3D Digital Elevation Map of the complex Mt. Vesuvius - Mt. Somma and the location (★) of the Vesuvian Observatory

The geometrical input to the full simulation is the Digital Elevation Map (DEM) of Mt. Vesuvius, shown in Fig. 13. The figure also shows the location of the Vesuvian Observatory. With respect to the numbers used in the model calculation (Fig. 12), a detector location at the Vesuvian Observatory implies a more ambitious task.

The full Monte Carlo simulation is based on a two step technique, already developed for studying the matter effect for the neutrino detection at Pierre Auger Observatory [31] and the relevance of the undersea site for the Mediterranean Neutrino Telescope [33]. As in the case of Fig. 12, as a starting point one assumes a given internal structure of the volcano including the presence of substructures to be revealed. In the first step we generate a large number of tracks, which proceed backwards from the detector and intersect the DEM and the substructures. For each track the layers of matter crossed and their density values are recorded. A huge set of tracks is produced in this way. As the second step, one runs GEANT4 which assumes a primary muon injected on any of the above tracks, represented by a sequence of layers of matter ending at the detector.

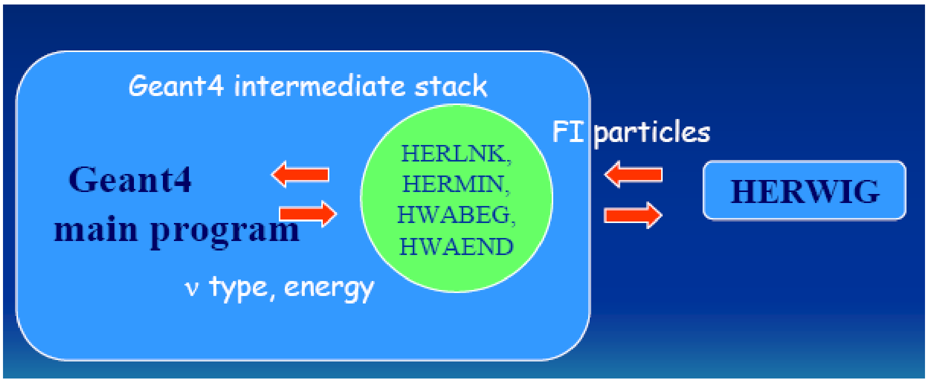

Fig. 14, The simulation program GEANT4 combined with the hadron generation code HERWIG.

At the present moment this technique is being applied by some of us to the undersea km^3 detector in the Mediterranean in order to perform the same study done for the Core Mantle Boundary determination by IceCube [29]. To this aim we have developed a new Monte Carlo code, which is obtained by combining (as sketched in Fig. 14) the hadron generation code HERWIG [57] and GEANT4 in order to be able to treat neutrino interactions. In this respect, we have already experience since some of us have developed a new version of the Air Shower simulation code CORSIKA [58], now able to treat neutrinos, by combining this Monte Carlo Simulator with the very advanced HERWIG.

The above Monte Carlo simulation technique is soon going to be applied to the muon radiography of Mt. Vesuvius.

5. The project

The success of the experiments conducted in Japan leads to envisage an increasing demand for muon radiography of volcanoes, with higher sensitivity. The spectrum of cosmic ray muons decreases according to the very steep power law $E^{-2.7}$, so that the flux of muons surviving in spite of the energy loss (of the order of 0.5 TeV/km) in the traversal of the volcano's edifice decreases very rapidly when one wants to investigate deeper structures.

The areas of the muon detectors so far employed have been of the order of 1 m^2. This relatively small area limits the application to small volcanoes or to the summit (a few hundreds of meters) of larger volcanoes. The extension of muon radiography to deeper structures requires an increase of the detector area by one order of magnitude or more. An increase of the detector area is also beneficial for reducing the measurement time, which in perspective should allow a quasi real-time monitoring of volcanoes. In general, to operate in a volcanic environment the detector must be characterized by portability, little need of maintenance and low or null electrical power consumption so as to allow the use of solar panels or other autonomous power supplies. In the case of the detector location at the Vesuvian Observatory, the electricity supply is available and the latter requirement does not apply.

A substantial progress in large area particle detectors has been done in Particle Physics for collider and neutrino experiments. The need to cover very large areas (thousands of square meters) has motivated the development of detectors technologically more advanced, cheaper and practically simpler to handle. A new generation of detectors for muon radiography may profit of these developments. In the following section, we will briefly describe some techniques for muon detection. Within the framework of the study, we will investigate which technique is most suitable for the investigation of Mt. Vesuvius itself and in general for muon radiography of other volcanoes.

In the first phase of the experimental program, we will accomplish the following tasks and explore the following methods.

First, we will develop a full Monte Carlo simulation code (as outlined in Section 4) for muon radiography at Mt. Vesuvius to estimate the muon transmission rate for different paths in Mt. Vesuvius and thus the detection sensitivity. Once this is achieved, one will be able to start to define the detector location: if the muon rate will prove to be sufficient, a measurement at the Vesuvian Observatory should provide useful information in the conclusive phase of the experiment. Otherwise a different, higher location has to be chosen.

Second, we will implement a muon measurement at Mt. Vesuvius to radiographically image the subsurface structure of the mountain, as described in Section 5.3. A segmented scintillation detector with a size of about 1 m^2 will be constructed and transported from Japan for this purpose. For this first measurement, the detector will be located at an altitude higher than that of the Vesuvian Observatory, so that the muon rate allows the use of a detector of ~ 1 m^2 area. Such a study should anyhow be included in a complete experimental program, where the subsurface structure is better investigated by placing the detector at an appropriate high altitude. Performing it from the beginning offers the bonus to make progress in the practical understanding of the experimental problems. The data analysis will involve the study both of the shallow structure of Mt. Vesuvius and of the requirements for the new detector. In addition to some exploratory imaging of the volcano, our experimental work will help to validate the Monte Carlo simulation, as well as to determine the capabilities of muon radiography as compared to the conventional geophysics techniques, such as seismometry and gravimetry.

The third task in the first phase concerns the study of the detector options, the choice of the detector technique and the design of the experimental setup.

In the second phase, should muon radiography prove to be effective to image the subsurface structure of Mt. Vesuvius, we will construct a detector with larger area (to be defined on the basis of the studies performed in the first phase) and attempt to obtain images of a deeper region of Mt. Vesuvius. We will interpret the images using our theoretical understanding of the volcanic processes involved. Owing to a capability of muon collection, muon radiography will provide a real time image of the internal structure of Mt. Vesuvius. In this regard, it is worth pointing out the ultimate aim of a real time monitoring of volcanic activities.

Already the observations of the subsurface structure which will be initiated in the first phase, we will see how to exploit the capability of obtaining three-dimensional images by making measurements from two or more different points of observation.

5.1 Detector techniques

In the following, we will briefly discuss two detection techniques which in principle could be applied, namely plastic scintillator strips and Resistive Plate Chambers (RPCs). Both are electronic techniques, which offer the advantage of real time data acquisition and online transmission to laboratories for analysis. In the first phase of the experiment, we will investigate whether other techniques could be exploited.

The very high spatial resolution of nuclear emulsion was evident in the beautiful results of recent muon radiographies of volcanoes [6-9]. Nuclear emulsions have undergone an impressive progress in their industrial production and analysis by high speed automated microscopes [59]. They offer the advantage of needing no electricity supply, but they do not allow an online analysis. For the domain of application of the proposed experimental program, we will focus the attention on electronic detectors.

The full detector will be formed by a sequence of detector planes, to form what in Particle Physics is called a “telescope”. A telescope is capable of measuring position and angle of particles, of which for muon radiography only the angle matters as the detector is essentially pointlike with respect to the mountain. We aim at an angular resolution of the order of 15 mrad, which at e.g. 1 km distance projects to a 15 m spatial resolution in the determination of internal structures. The deterioration of the spatial resolution due to the multiple scattering in the rock will have to be estimated.

5.1.1 Plastic scintillator strips

The early muon radiographies of volcanoes made use of 10 cm wide plastic scintillator strips, covering a total area of the order of 1 m^2. Each strip was read by a photomultiplier (PMT) through a light guide.

The neutrino oscillation experiments MINOS at Soudan mine [60] and OPERA at the Gran Sasso National Laboratory [61] have employed on a very large scale plastic scintillator strips with readout by optical wavelength shifting fibres and multianode PMTs. This has motivated several technical developments of which muon radiography could profit. In MINOS, plastic scintillation strips are used for muon tracking through its 31 m long muon spectrometer, where the bending field is provided by magnetized iron toroids having a 8 m transverse size. In OPERA, plastic scintillator strips are used in the so called Target Tracker which predicts in real time the location of the event in the nuclear emulsions, to guide their analysis. The plastic scintillator strip systems of MINOS and OPERA are conceptually similar.

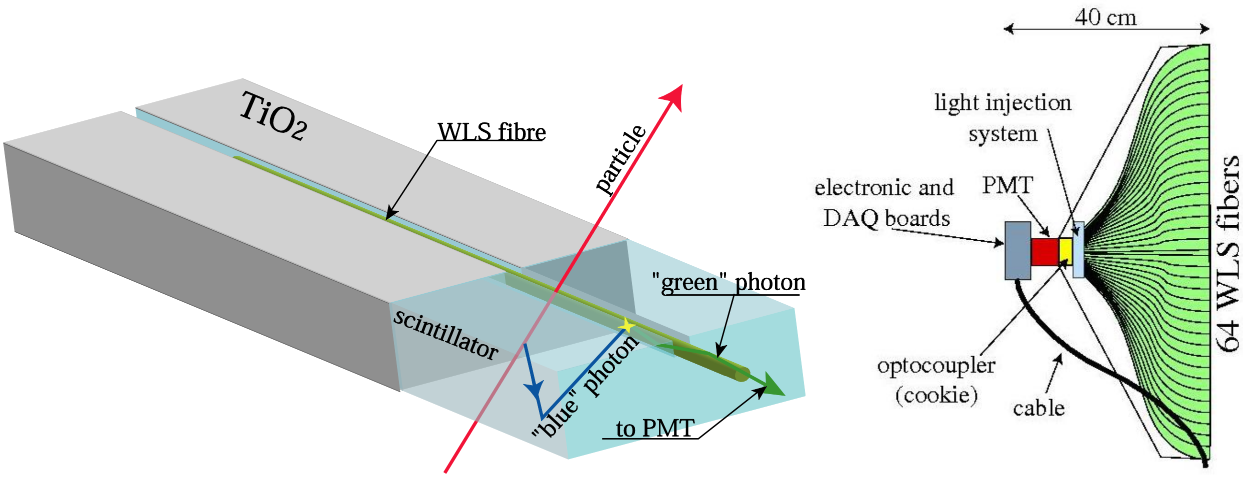

Fig. 15. The plastic scintillator strips (left figure) of the OPERA neutrino experiment and their readout by optical wavelength shifting fibres and multianode PMT (right figure).

Fig. 15 shows the scintillator strips of the OPERA experiment and their readout. Each strip is 2.6 cm wide and about 7 m long. A groove in the strip allocates a wavelength shifting optical fibre. The fibre conveys the optical signal to a multianode PMT, which reads the signal of 64 strips. A mechanical module thus consists of 64 strips and their readout. Modules are assembled together, to form planes with approximate size of 7 x 7 m^2. Two planes of strips, with horizontal and vertical orientation, are grouped together to predict the event location in each plane of emulsion detector. In total, the plastic scintillator strips cover an area of 2,900 m^2, very large compared to our needs.

An interesting possibility comes from the design of the scintillators of the inner detector of the Minerva experiment [62-64]. That experiment features planes of extruded scintillators of isosceles triangular section (3.3 cm base, 1.7 cm height), readout by embedded WLS fibers running in a 2.6 mm hole at the centre of the strip. The fibres are coupled to multi-pixel photo-detectors. The geometrical assembly of the scintillators, shown in Fig. 16, allows a spatial resolution which is determined by the charge sharing between the two scintillators traversed by the particle, thus significantly improving the spatial resolution obtainable with squared-section scintillators of similar transverse dimensions.

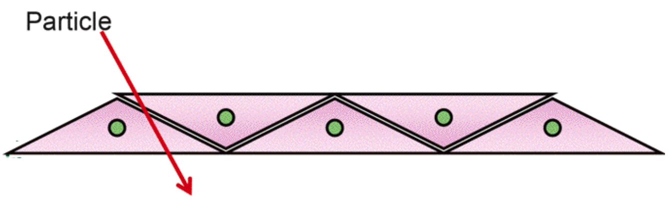

Fig. 16. The scintillators of the MINERvA inner detector.

A plastic scintillator detector requires a minimal maintenance, has a low power consumption and is relatively insensitive to ambient conditions. Detector planes with an area of ~50 m^2 area have been realized, as reported above. The limitation in size mainly comes from light attenuation. Plastic scintillator strips can be considered as our baseline detector option.

5.1.2 Resistive Plate Chambers

Fig. 17 shows the cross section of an RPC. The gas flows in a 2 mm gap, where an electric field is created by “resistive” electrodes which are transparent to the fast electrical signal produced by the passage of a charged particle. The signal can thus by readout by induction on metallic strips situated outside the chamber. The time resolution is about 1 ns. A single chamber allows the readout in two coordinates, by strips situated on either side of the chamber.

The RPCs are relatively cheap, light and easy to handle. They have been extensively used for large muon detectors in collider experiments and neutrino experiments. At LHC, both the ATLAS [65] and CMS [66] experiments make use of RPCs. In the following, we outline the features of the RPCs of OPERA.

In the OPERA RPCs, the x and y coordinates are read by 2.6 wide strips. Special chambers are readout by strips inclined by $\pm 45^0$, to resolve ambiguities in the track reconstruction. Each single chamber has an area of about 3 m^2. Several chambers are assembled in walls of about 9 x 8 m^2 area. The total area covered by the OPERA RPC system is 3,200 m^2.

A large detector area can be realized by straightforwardly patching up chambers. The temperature range for a good operation of RPCs is 10-35 ^{0}C. Moreover, RPCs need HV and gas supply. These constitute relevant inconveniences in relation to their portability in a volcanic environment. At the Vesuvian Observatory or in locations with similar facilities, the inconvenience is of minor importance.

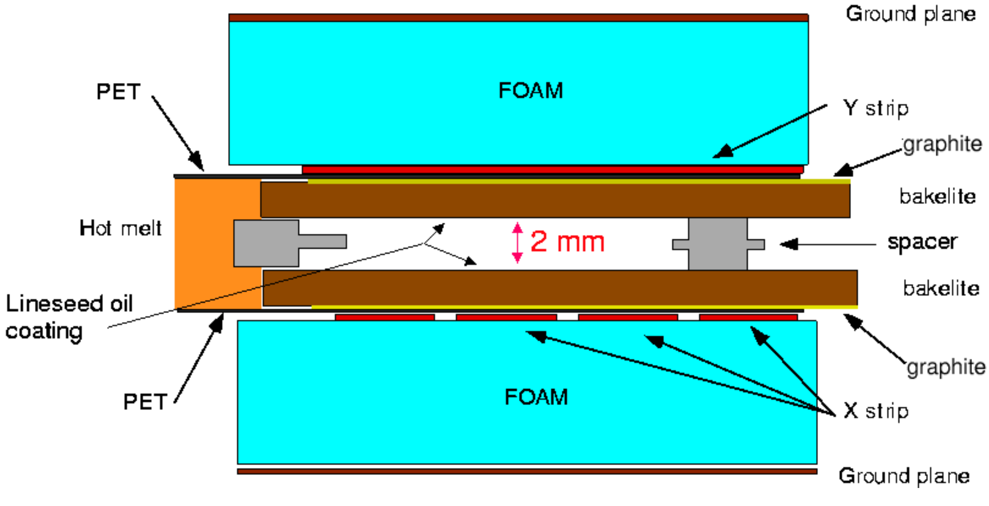

Fig. 17. The cross section of a Resistive Plate Chamber with its associated x-y strips, external to the HV chamber, for the inductive readout of the signals in two coordinates.

5.2 The muon detector and its location

From a practical point of view, a location of the detector at the Vesuvian Observatory presents obvious practical advantages and should thus first be considered as the baseline option.

Mt. Vesuvius is 1280 m high. The bottom of the caldera generated by the collapse of the conduit is at 950 m altitude. The 600 m altitude of the Vesuvian Observatory would allow investigations at larger depth (of the order of 200 m below the bottom of the caldera) in the volcano edifice than so far performed and thus require a detector of considerably larger area than for previous observations. In considering the Vesuvian Observatory as a possible location, one has to account for the presence of a 870 m high secondary cone (originated in the 1895-99 eruptions and called Colle Umberto) in the direction of Mt. Vesuvius. The full Monte Carlo simulation will allow the estimate of the flux of quasi horizontal muons (strongly attenuated in the traversal of the mountain) at the location of the Vesuvian Observatory and determine whether this flux is sufficient for a measurement or a location at higher altitude has to be chosen. In the choice of an alternative detector location (and in a future choice of further locations for the observation of structures in space and not only in a projection) one has to pay attention to the muon absorption in Mt. Somma before the traversal of Mt. Vesuvius and avoid it as much as possible.

Given the availability of standard electricity supply in the baseline detector location and possibly other locations, as already discussed we are envisaging the use of an electronic technique. In view of a future use in remote locations around Mt. Vesuvius or elsewhere, within practical possibilities we will design the detector with minimal requirements in electrical power so that the electricity could be supplied by solar panels or other means. We will also pay attention to the ease of installing the detector in any location of practical interest.

The detector itself could consist of at least two modules (each providing the two coordinates x and y) having 10 m^2 area or more. The addition of more planes provides redundancy in tracking, thus improving the background rejection and to some extent the angular resolution. A question to be addressed is the shielding from the soft component of the radiation. In previous observations, iron plates have been inserted in between detector modules to ensure that only muons provide straight tracks and are thus reconstructed. In addition, low hits multiplicities have been required in order to reject showers.

5.3 The plan for the first observations at Mt. Vesuvius

A comparison of Figures 1 and 8, as well as of Figures 13 and 17, shows that the morphology and size of the summit and of the caldera of Mt. Vesuvius are similar to those of Mt. Asama, where muon radiography was performed with ~ 1 m^2 detectors [6,7]. By appropriately choosing the altitude and location of the detector at Mt. Vesuvius, one can therefore reproduce the experimental conditions at Mt. Asama and , with a similar detector, conduct interesting observations in imaging the subsurface structure.

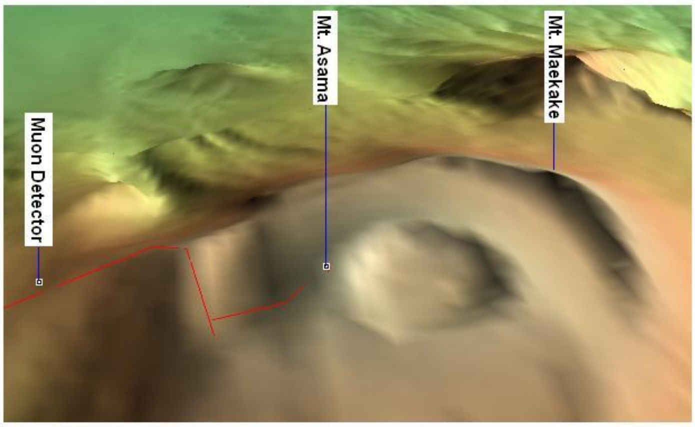

Fig. 17. Digital Elevation Map of Mt. Asama

For this measurement we plan to use the scintillator detector which is now used for observations at the Satsuma Iwo-jima volcano, which are supposed to last about one year and to be completed in early 2009. The measurement can be performed with a short time scale. It will contribute to the preparation for further observations at Mt. Vesuvius and will give the first results of the program of observations.

The apparatus has been set up in the framework of the ERI, JST (Japan Science and Technology Agency) and JSPS (Japan Society for the Promotion of Science) program by H.K.M. Tanaka of ERI. The apparatus consists of arrays of 7.8 cm wide plastic scintillator strips, equipped with power-effective photomultipliers and FPGA (Field Programmable Gate Array) electronics. A single anode photomultiplier tube with 10 dynodes has been developed for this application, so that one can set a relatively high threshold level to remove low-level noise and operate with a low power consumption although at that site the electricity is supplied by the net. Two detector planes of ~1 m^2 area, each consisting of an array with vertical strips and one with horizontal ones, are placed at 2 m distance one from the other. Taking into account that the track position given by the scintillator strips is quantized and cannot be treated by the standard rules of rms error propagation, the effective angular resolution of the muon detector is about 40 mrad.

This "digital muon camera" has been placed at the foot of Satsuma Iwo-jima volcano by one of the collaborators of H.K.M. Tanaka to survey the inhomogeneous structure of the mountain.

They will study the feasibility of using an azimuthally isotropic flux of cosmic-ray muons in the energy range up to a few TeV. The flux normalization comes from muons at the same azimuthal angle not traversing the mountain.

The muon detector is installed in a transportable house located about 1.3 km from the summit crater of Mt. Iwo-dake. The 40 mrad angular resolution of the muon detector corresponds to a spatial resolution of ~50 m at a distance of 1.3 km. The measurements would be ideal for studying the shallow structure of the crust at sites which cannot be well resolved because of their strong structural heterogeneity and potential difficulty to be accessed, and which therefore cannot have their structure determined by conventional electromagnetic or seismic techniques. A photograph of the digital muon camera is shown in Fig. 18 together with a map indicating the location of the camera. The apparatus is fully equipped and operational. At Mt. Vesuvius one has to provide the local infrastructure, such as detector housing, electrical power and data transmission system.

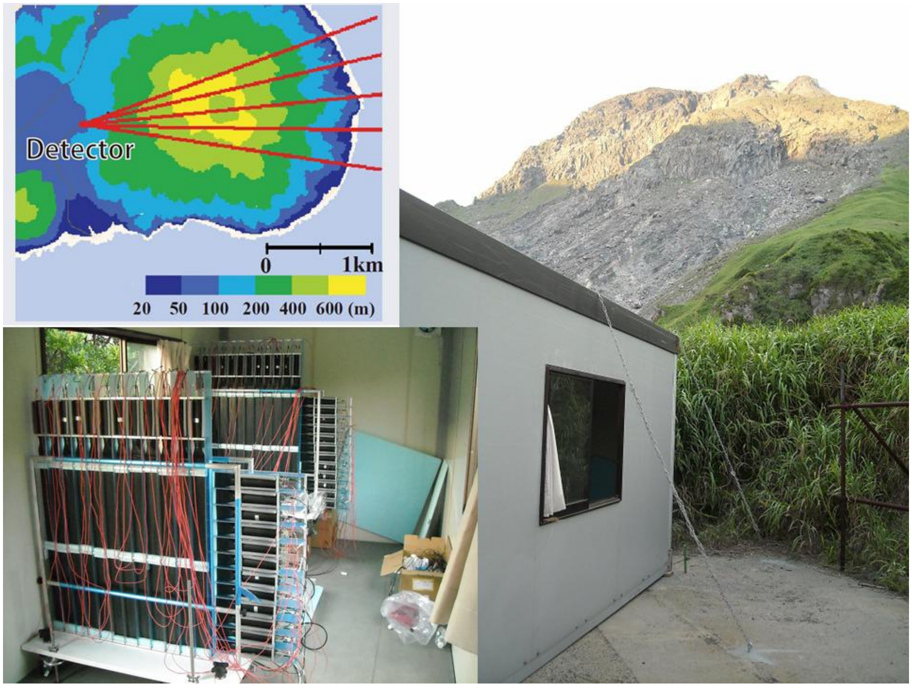

Fig. 18. The experimental set-up for the muon radiography of the Satsuma Iwo-jima volcano.

The apparatus will be transported to Mt. Vesuvius from ERI and will be set up there with the participation of the ERI group. It is expected that a graduate student from ERI will be a full time member of the research team. The volcanologists of the Collaboration have a deep knowledge of Mt. Vesuvius and will contribute to the analysis of the data and to their interpretation on the basis of independent geophysical explorations.

The detector will offer the possibility of imaging the subsurface structure of a Mt. Vesuvius such as the shape of the higher part volcanic conduit. We will be able to validate the Monte Carlo simulation as well as understand the time and detector areas required for real time measurements in other locations. The measurement will thus provide useful information concerning detector options, choice of the detector technique and design of the experimental setup in the next phase of the experiment.

6. The Collaboration

The Collaboration comprises: the Japanese group which has initiated the field of muon radiography by cosmic ray muons and is active on Japanese volcanoes; a French component consisting of volcanologists and a particle physicist, which has plans for observations at La Grande Soufrière on Guadeloupe in the Caribbean and is constructing a detector for this purpose; an Italian component consisting of volcanologists and particle physicists, including members of the Vesuvian Observatory; a particle physicist member from Spain. The Collaboration intends to join the efforts for the development of muon radiography and its application, in particular for volcanoes of specific interest for its members.

7. Conclusions

The studies conducted in Japan have opened the way to a new technique for investigating the inner structure of the edifice of volcanoes, the radiography by cosmic ray muons. In general, muon radiography is likely to have a considerable expansion for the study of volcanoes and for other applications.

The investigation of the internal structure of the edifice of Mt. Vesuvius at larger depths than in previous radiographies of volcanoes is a real challenge, also in relation to the morphology of the complex Mt. Vesuvius – Mt. Somma, and is motivated by a high social and scientific interest. It requires a muon detector area one order of magnitude or more larger than in previous investigations, in order to cope with the strong reduction which the muon flux suffers in the traversal of the volcano's edifice. The detector development and construction will exploit the experience in Particle Physics. It can be of general interest for a new generation of muon radiographies of volcanoes. Large detector areas allow the reduction of the measurement time and therefore also go in the direction of using muon radiography for monitoring purposes. Our baseline option is the use of plastic scintillator strips.

We will first examine a location the detector at the Vesuvian Observatory, which presents obvious advantages. Depending on the results of the muon flux estimates planned in the first phase of the proposed program, we may be led to locate the detector at a higher altitude. We plan to perform first observations with a detector having an area similar to that used in previous radiographies, located at an altitude appropriate to explore the subsurface structure of Mt. Vesuvius.

The developments and the observations with a large area detector at Mt. Vesuvius, with international participation, are intended also in view of the subsequent application to other volcanoes. Of special interest in the application to Strombolian volcanoes.

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