We now have tools that go beyond imaginative speculation to find out exactly what is happening inside volcanoes, but unfortunately they are still very limited. Current methods are indirect. For example, one method uses small explosions to propagate small tremors around a volcano, which yields information from the way that these artificial seismic waves are reflected (like echoes) by rocks of different density. Using complex mathematics, this data can provide details of the internal structure of the volcano.

A new imaging technology

The aim of our project, which is a collaboration between scientists in Italy, France, the USA and Japan, is to further develop a new way to ‘see’ inside volcanoes directly. We want to produce shadow pictures, similar to the way that X-rays allow us to see inside the human body. But instead of X-rays, we are using muons (penetrating particles with a mass about 200 times that of electrons) – hence the project name of Mu-Ray. The technique is known as muon radiography.
Muon radiography was first used in 1971 – not for volcanoes, but for investigating the interior of the pyramid of Chefren at Giza, Egypt. The Nobel-prize winning physicist Louis Alvarez placed a muon detector inside the pyramid to pick up changes in muon flux (rate of muon flow) that could indicate the presence of a hidden burial chamber. However, none was found.

In 2007, Hiroyuki Tanaka and collaborators from the University of Tokyo were the first to apply this technique to volcanoes. They carried out radiography of the top part of the Asama volcano in Honshu, Japan.
which revealed a region with rock of low density under the bottom of the crater. The presence of low-density regions 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 indeed produce useful images of the internal structure of volcanoes.

The really important advantages of muon radiography of volcanoes are two-fold. First, whereas current indirect methods can provide information to a spatial resolution of some 100 m, muon radiography can be up to ten times more specific, mapping internal structures to a resolution of some 10 m. Second, muon radiography offers the possibility of continuous monitoring, thus potentially revealing the evolution of structures over time. The time resolution depends on the thickness of the rock traversed by the muons: the thicker it is, the fainter the muon flux and the longer it takes to accumulate enough muons for a picture. The time needed can thus be weeks, months or years.

The shower of particles produced when a cosmic ray, a primary particle accelerated by mysterious mechanisms in the distant Cosmos, reaches us and interacts with an atomic nucleus in Earth’s atmosphere. Muons are indicated by the symbol \( \mu \); other particles shown are photons \( (\gamma) \), pions \( (\pi) \), neutrinos \( (\nu) \) and energy \( (e) \).
Muon radiography is now being used for volcanoes around the world: in the Lesser Antilles, at the Puy de Dôme in Central France, and in our very challenging work on Vesuvius with the Mu-Ray project. The images are produced using detectors called muon telescopes, which use technology developed in particle physics and play the role of the X-ray film in conventional radiography. The telescopes detect near-horizontal muons emerging from the volcano’s edifice, having passed right through it. By reconstructing the path of each single muon through the volcano, the apparatus reveals the amount of muon absorption in each direction. Denser rocks absorb more muons, so a map of muon fluxes gives a negative image of the rock densities inside the volcano. Such images cannot help to predict when an eruption might occur, but – combined with other observations – can help to foresee how one could happen.

**Imaging Vesuvius**

So, what about Vesuvius? This volcano is a special challenge, not only because it represents the highest volcanic risk in Europe, but also because of the mountain’s unusual structure. Vesuvius is in fact situated within the remnants of a much larger volcano, Mount Somma. Moreover, inside the summit of Vesuvius is a crater that is 500 m wide and 300 m deep: this means that, to look below the bottom of the crater, muons have to penetrate deep into the mountain, through almost two kilometres of rock, to reach the detector on the opposite side of the volcano. Only muons of very high energy travelling in a near-horizontal direction are able to pass through all this rock, so their flux at the detector is very low, making imaging extremely difficult. This explains why the project – and the development of muon radiography – is extremely challenging.

To look inside Vesuvius, therefore, we need to develop a new type of muon telescope. To detect enough particles of such low flux to produce an image, this apparatus must cover a much larger area than previous muon telescopes. Substantial improvements are also needed to distinguish the experimentally important particles from background muons – which we plan to do by measuring each muon’s time of flight through the telescope to confirm that it really has the right direction to have passed through the volcano.

A prototype telescope with a detector area of just 1 m², compared to 10 m² or more to be covered by the final telescope array, has been recording data at Vesuvius since Spring 2013. The data is currently being analysed.

The detectors consist of plastic scintillator strips – a technology borrowed from particle physics. These strips can be used to cover large areas and provide long exposure times, and they are robust enough to withstand volcanic conditions. Of practical importance too are the telescope’s low energy consumption, enabling it to be powered by a solar panel, and its portability, so that it can be used in different locations. Depending on funding and the experience gained with the prototype, we hope as the next step to construct two telescope arrays, each with total areas of 4 m², to record data for one year or more.
New frontiers

Meanwhile, particle physicists and volcanologists continue to work together in muon radiography. As well as providing a powerful tool for the study of geological structures, this expanding field also has potential industrial applications, such as seeing inside nuclear reactors or determining the remaining thickness of the wall of an iron furnace, which can then be replaced at the right time.

Alongside these possibilities, there is another developing technology that promises imaging on an even larger scale: neutrino radiography. With their extraordinary penetration power, neutrinos produced by cosmic rays and passing through Earth itself could at some future date provide information about the density of the core of our own planet.

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Web reference

w1 – Learn more about the Scienza e Scuola (science and school) project. See: http://scienzaescuola.fisica.unina.it

Resources

To learn more about the Mu-Ray project, see the project website. http://mu-ray.fisica.unina.it

In its most famous eruption, in 79 AD, Mount Vesuvius destroyed the Roman town of Pompeii. The Last Days of Pompeii by Karl Briullov (1799–1852)
Details can also be found in:


For more technical details about the Mu-Ray project, see:


Beauducel et al. (2008) Muon radiography of volcanoes and the challenge at Mt. Vesuvius. The article can be downloaded from the Mu-Ray project website (click on ‘Read the complete proposal’). See: http://mu-ray.fisica.unina.it

The website of the European Space Agency (ESA) offers multimedia background information about cosmic rays. See: http://esamultimedia.esa.int/multimedia/edu/Cosmic_Rays.swf or use the shorter link: http://tinyurl.com/m6ap2c3

ESA’s Eduspace website offers school-level information about volcanoes, including how they are monitored. See: http://www.esa.int/SPECIALS/Eduspace_Disasters_EN/SEM3WAMSNNG_0.html or use the shorter link: http://tinyurl.com/k6ep7tb

To mimic in the classroom how volcanoes are traditionally investigated, by monitoring the characteristic way seismic waves travel through rocks of different density, see:


With its most famous eruption, in 79 AD, Mount Vesuvius destroyed the Roman town of Pompeii. To learn how modern scientific analyses are casting light on the ancient town, see:


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Paolo Strolin is an emeritus professor at the University of Naples Federico II, Italy. His main scientific background is particle physics, in particular neutrino physics. His interest in education has led him to be involved in the Scienza e Scuola (science and school) project, which links school teachers, school students and professional researchers to encourage and nourish young people’s interest in and knowledge of science.\(^1\)

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*Photo of the Cleveland Volcano, Aleutian Islands, taken from the International Space Station on 23 May 2006. The volcano emitted a plume of ash but did not erupt.*

Image courtesy of NASA