The pyramid detectives

Lucina Melesio explores how physicists are mapping the internal structures of ancient pyramids in Mexico and Central America using muons – potentially revealing hidden chambers that could finally lead archaeologists to where ancient rulers are buried

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When the Aztecs first happened upon a certain valley near modern-day Mexico City back in the 14th century, what they saw must have come as a shock. Before them lay a vast deserted city, comprised of such grand monuments that the tribe believed it to be the site at which the gods had created the universe. They named it Teotihuacan – "The City of the Gods".

Today, tourists are similarly awed as they stroll down the Avenue of the Dead – the two kilometre-long processional road at the heart of the city. Of the numerous monumental buildings that line this street, two immediately catch the eye because they are so much bigger than the rest: the Pyramid of the Moon and the even larger Pyramid of the Sun, which by volume is the third-largest pyramid in the world.

Archaeologists have scrutinized the city over the years and learned a lot, finding, for example, that Teotihuacan was established in around 100 BC, before growing to become one of the largest cities of ancient times with at least 125 000 people. But one question remains as mysterious as it was in the time of the Aztecs: where are the ancient rulers of Teotihuacan buried? We know that Egypt's pyramids were built as tombs for the country's pharaohs, but the past rulers of Teotihuacan are nowhere to be found. What's more, there is no sign that the Pyramid of the Sun contains any burial chambers at all – or so it would seem from the outside.

To find out once and for all what – if anything – is inside the Pyramid of the Sun, in 2000 a team of physicists from the National Autonomous University of Mexico (UNAM) hung up their lab coats, strapped on their boots and helmets and went to Teotihuacan. Taking advantage of the muons that continually shower the Earth's surface, the researchers set up an imaging tool that would allow them to explore the insides of the ancient structure without moving so much as a single pebble. But their method would take time and patience, relying as it does on building up a signal very slowly. It will have been more than a decade before they are ready to reveal what the Sun Pyramid conceals within.

The principle behind the technique involves placing a muon detector within or beneath a pyramid

Muons to the rescue

The idea of imaging the internal structures of pyramids using muons was developed in the 1960s by Luis Alvarez at the University of California at Berkeley, who also won the 1968 Nobel Prize for Physics for developing the hydrogen bubble chamber and who later postulated the idea that the dinosaurs became extinct after an asteroid crashed into the Earth. Muons are charged elementary particles that continually rain down from the sky where they are created in muon–antimuon pairs as by-products of cosmic rays interacting with the atmosphere. Roughly 200 times heavier than their cousins the electrons, muons are able to penetrate dense materials such as rock, but in doing so they gradually lose energy and slow down.

The principle behind Alvarez's pyramid-imaging technique involves placing a muon detector within or beneath a pyramid and measuring the energies and trajectories of the incident muons. When a muon passes through a material, the amount of energy it loses increases with the density of the substance, which means that the energy of a muon travelling through an air-filled hidden chamber will be hardly affected at all. By comparing the muon data with simulated data based on what would be expected if the pyramid were solid through and through, researchers can pinpoint differences in density within a structure that might indicate an archaeologically significant feature. Named "muography", the technique is similar to radiography, except that in muography a 2D image is taken of a pyramid's insides using muons, whereas in radiography a 2D image is taken of a patient's insides using X-rays.

Alvarez first developed the technique in the late 1960s in a search for hidden chambers inside the Pyramid of Chephren in Egypt. He set up a muon detector inside an inner chamber and found "nothing", as some people incorrectly put it. Arturo Menchaca, leader of the physics team at Teotihuacan, recalls making the mistake of saying this to Alvarez back in the 1970s. "He furiously corrected me: he had *demonstrated* there was nothing inside the pyramid," says Menchaca, who at the time was a postdoc at the Lawrence Berkeley Laboratory with an interest in this new field. Menchaca explains that this is no subtlety:


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Hidden secrets
The Pyramid of the Sun at Teotihuacan in Mexico became a physics experiment for more than a decade. Muons were detected in a chamber underneath it in an attempt to map the pyramid's internal structure.

finding there is nothing inside these huge structures is incredibly useful to archaeologists, who can then conclude that there are no hidden wonders for them to explore and can move on to other sites.

Adventuring below

The "Alvarez test" – as Menchaca nicknamed it – suited the Sun Pyramid well since beneath the massive structure, which is 75 m tall and 225 × 225 m at its square base, is a deep underground tunnel leading towards the pyramid's centre and ending with a small clover-shaped chamber. The tunnel was most likely excavated by humans to get soil and rubble to build the pyramid, and is centrally located 6 m beneath the pyramid's structure. The existence and position of the cavity was a stroke of luck because it is a rather uncommon feature of American pyramids but is the ideal place in which to position a muon detector. (Not all pyramids are so fortuitously designed – see box about pyramids at the La Milpa site in Belize on p26.)

Besides updating Alvarez's original experiment with modern technology, one of the major issues Menchaca's team has faced over the last decade's work has been adjusting to the on-site conditions, which were extremely different from those in the lab. Needless to say, the chamber wasn't exactly designed to fit a physics experiment inside it. Access to the tunnel is through a small hatch at the base of the pyramid that leads to a two-storey metal staircase down into pitch darkness. The tunnel leading to the chamber is narrow and irregular – in some parts

Muons at La Milpa

Roy Schwitters

Francisco Estrada Belli / La Milpa Archaeological Project, Boston University/Norman Hammond and Gair Tourtellot

Tough terrain The pyramids at La Milpa in Belize are buried under jungle – not the easiest place to set up a physics lab.

The researchers at Mexico's ancient city of Teotihuacan are not the only group using muons to image pyramids in the Americas. Another team of physicists, led by Roy Schwitters from the University of Texas (UT) at Austin, travelled this summer to a remote Mayan site in Belize where they installed two muon detectors in search of royal tombs. "All over Central America there are things that look like jungle-covered hills, but there are rubble-covered marvellous pyramids underneath that haven't been exposed at all," says Schwitters.

The site, called La Milpa, lies in a jungle near the border with Guatemala and Mexico, where the team's target is a tree-covered mound about 20 m high. Simply named "Structure 3", it is one of four large structures likely to hold pyramids within. "Mayan pyramids are built like nested dolls – there is one structure inside of the next," says Fred Valdez, an archaeologist from UT Austin who is in charge of the site and is collaborating with Schwitters' team. "The detector will allow us to see internal walls and internal staircases; it may detect voids or holes within the structure, and if they are sizeable, they might represent tombs."

Mayan pyramids typically contain royal tombs, but in La Milpa, the third-largest Mayan site in Belize, archaeologists have yet to find any. "We know there are tombs in these buildings; the question is: *where* are they located?" asks Valdez. Tombs are often discovered by sheer luck, with archaeologists at La Milpa unable to use standard technologies such as ground-penetrating radar that require flat terrains free from rocks and roots to operate. But by using "muon-tomography" (a 3D version of tomography – see main text), which suits large volumes and uneven terrains, archaeologists will find out exactly where to look.

The two pyramids that have been imaged using muons previously – the Chephren and Sun pyramids – have tunnels running underneath or inside them, in which the detector was placed. Structure 3 does not have such a tunnel, so instead, Schwitters' team placed two solar-powered detectors – each the size of a large household boiler – in trenches either side of the mound. Each detector will collect muons crossing sideways through the pyramid, and once the data are put together they will create a stereographic 3D image of its internal structure. The system is fully stand-alone because the local climate is so rainy that the team can work on-site only during a single eight-week window each year. The researchers plan to return to collect their first data in 2015.

researchers had to line up and crouch down just to get through. The detector, which is 1.5 m^3 in size, could not have fit through the tunnel in its final form, so had to be custom built so that its smaller constituent parts could be taken through one by one, before being re-assembled inside the chamber, within a small shed. The team managed to get power from the electrical grid about a mile away by running cables through hosepipes all the way to the pyramid. And since oxygen became scarce towards the far end of the tunnel, they installed a pump to send fresh air throughout the entire passage, while carbon-dioxide monitors and oxygen tanks were placed in critical areas as a safety measure.

It took the team almost a decade to custom-design the final detector. As the imaging angle of a muon detector increases with its surface area, the researchers scaled up small models until their detector was big enough to look at almost the entire Sun Pyramid at once. They would have to tilt the detector a little bit to get a glimpse of the few remaining blind areas, but otherwise it was completely stationary. The final detector was an array of rectangular multi-wire chambers, and since tiny drops of water condense all over the internal rock walls, these chambers had to be made robust enough that they would be unaffected by the humid conditions.

Waiting for the final verdict

After a decade's work, the physicists at the Sun Pyramid have now packed up. Having collected all the data they need, they are finishing their analyses and preparing to publish their results. Their most significant finding, which Menchaca presented at a UNAM conference in February, is that within the pyramid they have found an area with a base the shape of an equilateral triangle with 60 m sides that is less dense than the rest of the structure. Since their image is

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2D, their data cannot tell them the height or volume of what they have found.

This preliminary result hit the headlines earlier this year, but – disappointingly for Menchaca – reports tended to focus on one alarming scenario out of several possible interpretations. The Sun Pyramid was reported as being at risk of collapsing "like a sandcastle", going with the scenario that, since the less-dense area is on the southern, sunnier side, the density difference is due to a drier area that might be weakening the entire structure. But the team is not ready to reveal its final interpretations just yet. "We reserve the right to declare whether or not we have found chambers within the pyramid until we finish our analysis and publish our results this year," says Menchaca. Before then, the team still has to finish analysing the data obtained when the detector was tilted towards the highest part of the pyramid.

Menchaca explains that while the sandcastle theory is one of many that are plausible, it is premature to jump to firm conclusions. After all, the muography is a 2D projection, so height distribution is indeterminable. "For all we know, this area we see might be an ancient nightclub," he jokes. "We won't be able to find out until we report our final results for the archaeologists to interpret and they decide the best way to physically probe into that area to get an actual glimpse of it." In the meantime, Menchaca assures us that he honestly doesn't think the pyramid will collapse. "My guess is that the Sun Pyramid will be here for the next 2000 years, just as always," he says.

The once-busy tunnel under the Sun Pyramid is now silent. The detector has been stripped of all its electronics. Some of the light bulbs that used to faintly light the way along the dark passageway are burnt out. And the ever-present hum of the oxygen pump has given way to silence. Soon the remains of the experiment will be removed for good, and the detector will be exhibited in the site's museum.

After more than a decade-long renaissance of pyramid detective work, we could be in store for some great revelations from the particle physicists who have gone out tomb-seeking. As we await the final report on the Sun Pyramid, and with the new detectors now collecting data at La Milpa in Belize, the collaboration between particle physics and archaeology is alive and well. ■