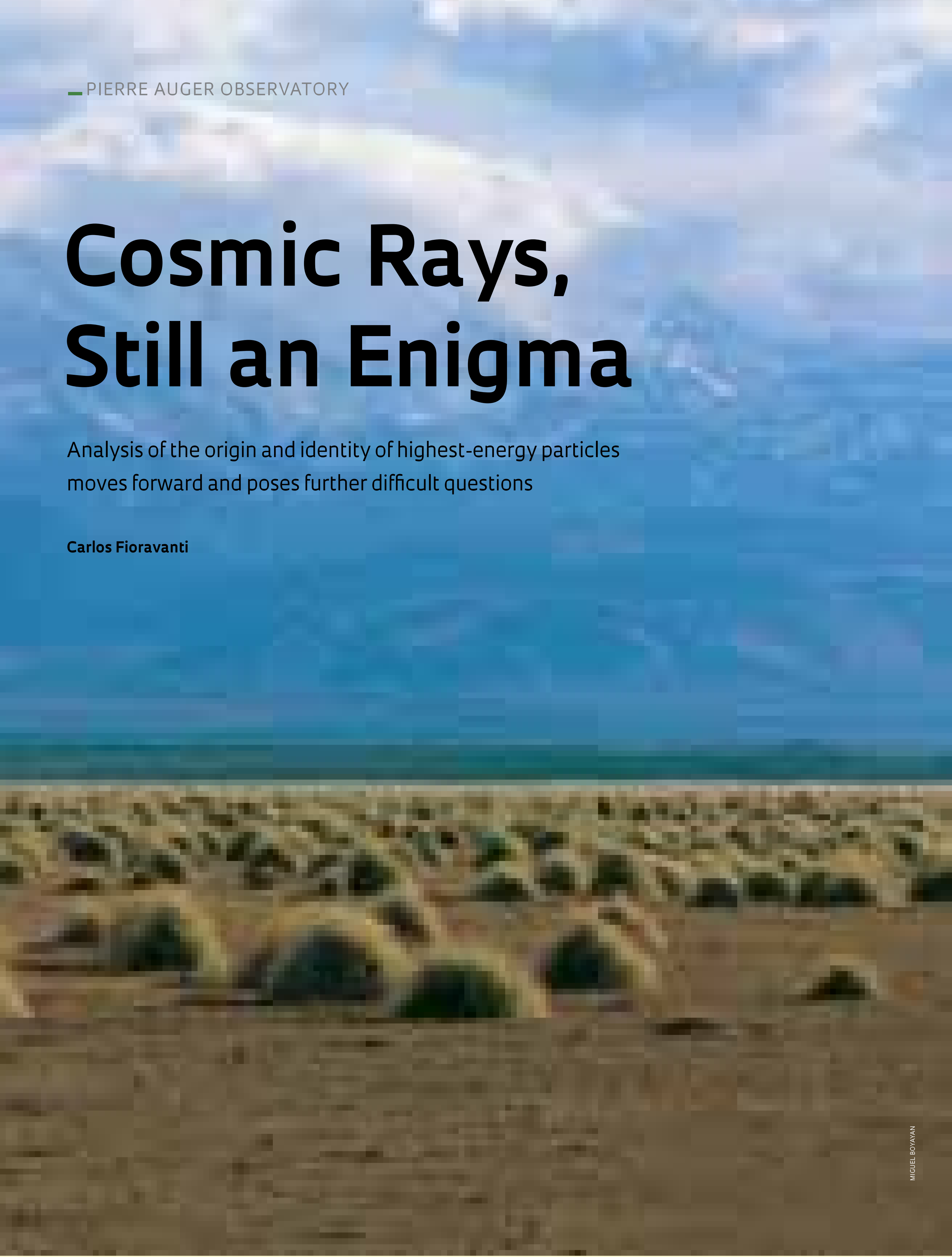
PIERRE AUGER OBSERVATORY

Cosmic Rays, Still an Enigma

Analysis of the origin and identity of highest-energy particles moves forward and poses further difficult questions

Carlos Fioravanti



MIGUEL BOYAYAN

A plain at the foot of the Andes: an ideal place to capture particles coming from space

Among the news items circulated by the Reuters international news agency on November 8, 2007 was an article entitled, “Cosmic Rays Believed to Start in Black Holes.” On the same day, the British magazine *The Economist* abandoned its customary caution with the headline, “They Came from Outer Space: A 40-year-old Mystery is Solved,” in reference to the possible origin of those particles. The findings from the work of an international team of physicists and engineers at the Pierre Auger Observatory in Argentina had enormous repercussion. The Auger website chose for publication 65 articles from newspapers and magazines from around the world to report the news, details of which appeared in the lead article in *Science* magazine the following day. The mystery, however, has still not been unraveled.

Four years later, there are still signs that active galactic nuclei, where black holes are formed, may really be the source of ultrahigh-energy cosmic rays, above 10^{19} electron volts (eV). “The signal is still there, but weaker,” said Carola Dobrigkeit Chinellato, a professor of physics at Brazil’s State University of Campinas (Unicamp) and coordinator of the São Paulo team. Of the nearly 450 authors of scientific articles referring to data obtained from the observatory, 30 are Brazilian, and 19 of these are from the state of São Paulo. Through an international collaboration that now includes some 500 physicists from 90 institutions in 19 countries, construction on the observatory began ten years ago at the foot of the Andes on a semi-desert plain on the outskirts of Malargüe in northwestern Argentina. The physicists began to collect data in January 2004 during the construction phase, which was completed in 2008.

The rate of correlation between cosmic rays and active galactic nuclei, which was 69% in 2007, fell to approximately 40% and stabilized at that level in the following years. During that time, the surface detectors and telescopes detected more particles, but the rate is still higher than the 21% attributable to pure chance. Unlike particle accelerator physicists, who can produce collisions between protons whenever they wish, the physicists at Pierre Auger have to wait until they arrive from the sky. Each year, only a few dozen of the highest-energy cosmic rays reach the top of the Earth's atmosphere. Each of these cosmic rays traverses the atmosphere and interacts with the nuclei of atoms and molecules of air, producing an atmospheric shower made up of billions of particles. Some of these particles will reach the 1,660 surface detectors, the so-called Cherenkov tanks, each of which holds 12,000 liters of highly purified water. The tanks' sensors detect the bluish light emitted in the water when electromagnetic particles traverse the tanks (*see illustration on the following page*).

Scattered over 3,300 square kilometers—double the size of the city of São Paulo—the surface detectors operate in combination with 27 fluorescence telescopes, known as Fly's Eyes. These telescopes are capable of recording the faint light emitted by nitrogen molecules in the upper atmosphere when they are excited by particles from the shower produced by a cosmic ray that has reached the Earth. Because they are so sensitive, the fluorescence detectors, installed on four buildings, work only in the dark on moonless nights, while the tanks capture shower particles all the time.

The Pierre Auger facility is the site of the first experiment to integrate the two independent methods of observation. Before that time they were used separately in smaller observatories like the Fly's Eye, which operated in the United States from 1981 to 1992 with 67 telescopes, and the Akeno Giant Air Shower Array (AGASA) in Japan, with 111 surface detectors. "A number of innovative details from the original design are now proving valuable," notes Carlos Escobar, the physics professor at Unicamp who coordinated the Brazilian team and handled negotiations with the construction firms working on the observatory in Argentina starting with the initial planning meetings. He was one of two Brazilian representatives, along with Ronald Shellard, a researcher from the Brazilian Center for Physics Research (CBPF) in Rio de Janeiro and current coordinator for Brazil's participation at the Auger site. Escobar has been working as an invited researcher at Fermilab in Chicago since April 2011.

Only one highest-energy particle per square kilometer per century reaches the Earth

RARE RAYS

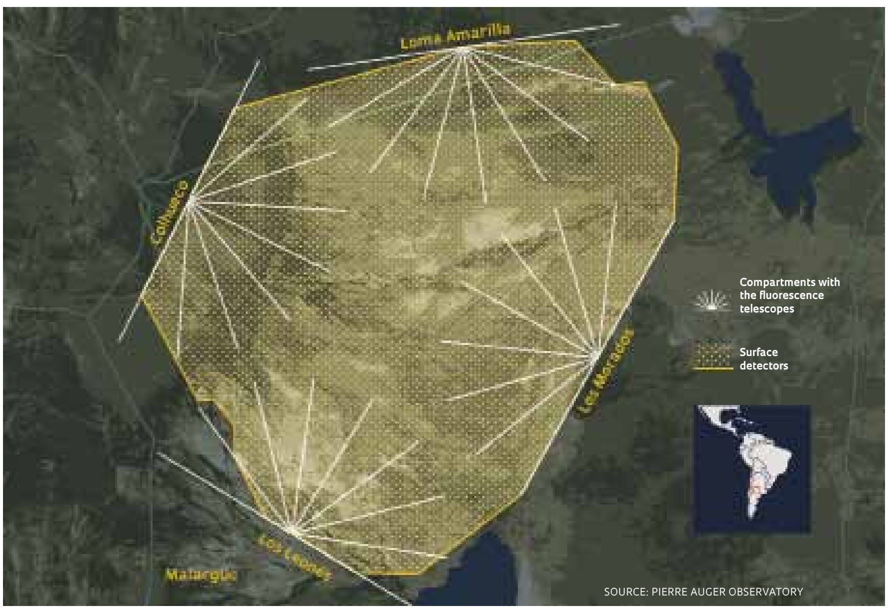
French physicist Pierre Victor Auger identified the showers of particles in a historic experiment conducted in the Alps in 1938. So many years later, the composition of the highest-energy cosmic rays remains unknown. The principal reason for this is that they are quite rare. The higher the energy, the rarer the particles. "When the energy increases tenfold, the number of cosmic rays that reach the Earth with energy above that value is one hundred times lower," Chinellato said. "The highest-energy cosmic rays have energy above 10^{19} eV, and only a few of them per square kilometer reach the Earth each year. For particles with energy above 10^{20} eV, the rate drops to one particle per square kilometer per century."

According to Chinellato, in the analyses of ultrahigh-energy cosmic rays detected at the Auger Observatory, the result of the correlation with active galactic nuclei strengthens the hypothesis that cosmic rays are protons, or hydrogen nuclei. "The rationale behind this interpretation is that the cosmic rays were likely to have been minimally deflected by the magnetic fields that they traversed, and that therefore they retained angular proximity with their possible sources," she said. "Had they been nuclei of heavier elements such as iron, for example, they would have undergone greater deflection in the magnetic fields, which would eliminate that correlation."

But things are not quite so simple. Observations of the development of particle showers by the fluorescence telescopes and comparisons with theoretical predictions indicate that cosmic rays—at least some of them—could be heavier nuclei such as iron, i.e., blocks of 26 protons and 30 neutrons. "That interpretation is fairly dependent on the validity of the theoretical models in the description of the development of the showers," Chinellato observes.

Ground detectors

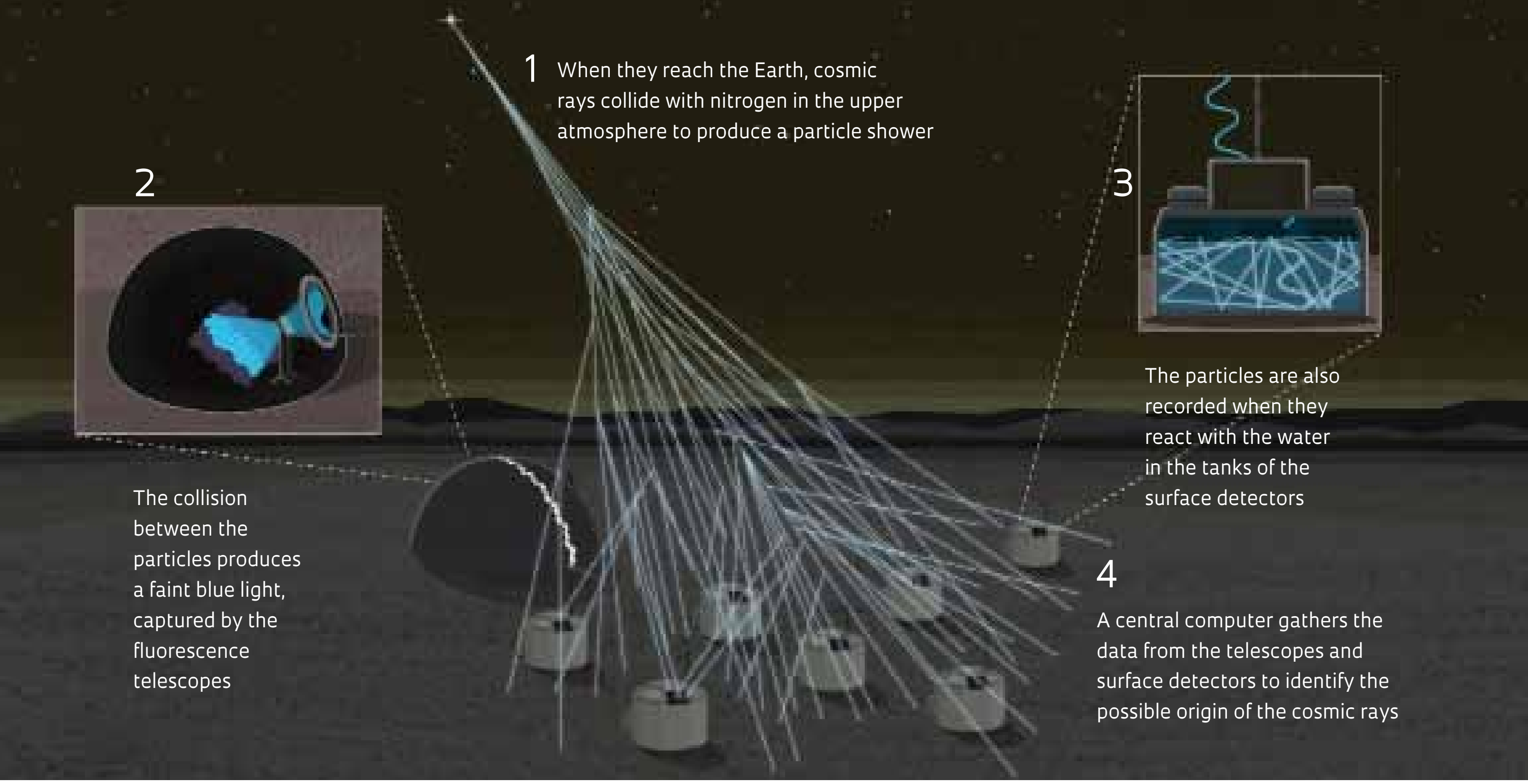
The Pierre Auger Observatory covers 3,300 square kilometers, double the size of the city of São Paulo and 10 times larger than Paris



SOURCE: PIERRE AUGER OBSERVATORY

Waiting for particles

The Pierre Auger Observatory combines two independent ways of detecting cosmic rays



"The theoretical models are based in part on extrapolation from observations in experiments with particle accelerators at much lower energies." In practice, for now we cannot simply choose one conclusion over the other.

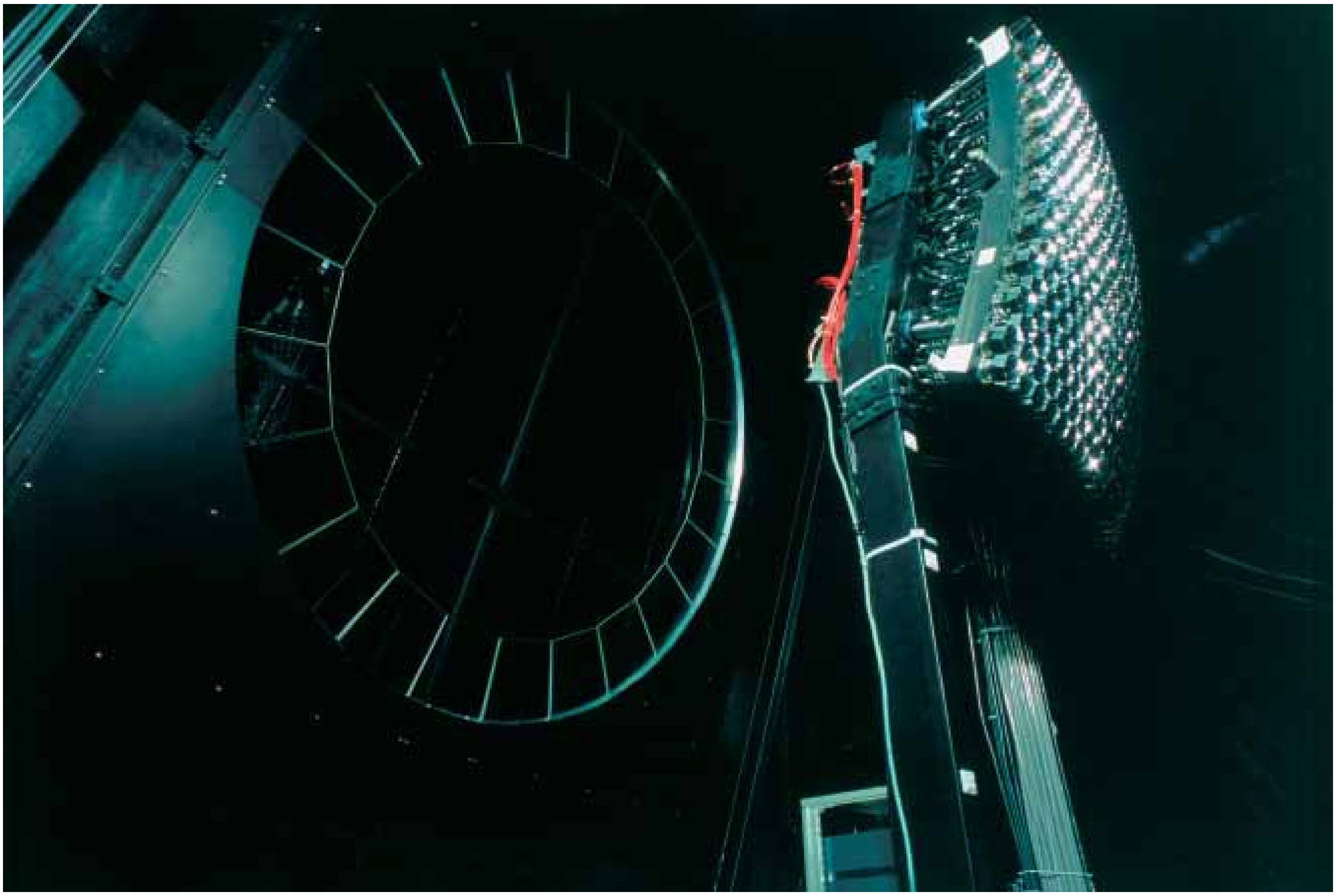
To arrive at a less uncertain conclusion, physicists will have to adjust, correct or expand these theoretical approaches in order to explain the identity of cosmic rays. Theoretical physics does not explain how cosmic rays can acquire an energy 100 million times greater than that of particles of the same type produced in the Tevatron, the world's most powerful particle accelerator located at Fermilab. In other words, the conceptual tools are limited and the options are still shaky. "Our data from 2007 further weaken the top-down models", Escobar said. Defended by other groups of physicists, top-down models assume the existence of particles with even higher energies than the ones detected, above 10^{20} eV. In eight to ten scientific articles published each year, the physicists at Auger have published details of these and other conclusions, and have presented potential new uses for the equipment, such as monitoring weather or the movements of tectonic plates.

The total energy levels in the particle collisions being analyzed are about 100 to 200 times higher than those produced in the Large Hadron Collider (LHC), the world's largest particle accelerator located at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. The LHC groups are also experiencing progress, setbacks and digressions in attempting to confirm the existence of the so-called Higgs boson, a hypothetical particle that could give other particles mass and confirm the formulas that physicists have worked with for 50 years. "Heraclitus said that nature loves to hide," says Escobar. "In order to identify precisely whether cosmic rays are protons or nuclei of iron, we will need another 15 years of data," he said. "When the observatory was being built, it didn't seem so, but at 3,000 square kilometers—the current size of the observatory—it's actually too small."

Built between 2002 and 2008, Pierre Auger is the largest cosmic ray observatory in operation. The area it covers is so large that even the most frantic motorcyclist zooming between cars in the city of São Paulo would be unlikely to see in one day all of the 1,660 cylindrical tanks, each measuring 3.7 meters in diameter and 1 meter high, spaced 1.5 km apart in the form of a triangular grid. In the past two years, Escobar says, the tanks have acquired more electronic devices and, in addition to recording the light produced in the collision with the water in the tanks, they are able to record the arrival of particles formed when cosmic rays break apart as they hit the Earth's atmosphere, thus reinforcing the debate around solving the identity of cosmic rays.

The electronic detectors in the tanks at the Pierre Auger Observatory are al-

INFOGRAPHICS TIAGO CIRILLO ILLUSTRATIONS DRUM



Brazilian participation in the Pierre Auger Observatory

INVESTMENTS
FAPESP, US$2.5 million; Finep/MCT, US$1 million CNPq, US$300,000;
FAPERJ: R$ 00,000

INSTITUTIONS
Brazilian Center for Physics Research (CBPF); Pontifical Catholic University – Rio de Janeiro (PUC-RJ); University of São Paulo (USP), Physics Institute, São Paulo; State University of Campinas (Unicamp); State University of Feira de Santana (UEFS); State University of Southwestern Bahia (Uesb); Federal University of Bahia; Federal University of the ABC (UFABC); Federal University of Rio de Janeiro (UFRJ)

COMPANIES
Alpina Termoplásticos; Rotoplastyc Indústria de Rotomoldados; Equatorial Sistemas; Schwantz Ferramentas Diamantadas; and Acumuladores Moura

ready capable of detecting showers initiated by neutrinos and photons in the upper atmosphere. Neutrinos are very low-mass particles and are extremely abundant, but less abundant than the particles of light known as photons. "Theoretical models now exist that predict that neutrinos and photons are produced by the same sources as cosmic rays or even during the propagation of cosmic rays through space, but so far we have not detected any of them reaching Earth," Chinellato notes. "The fact that we have not detected any is also significant."

As the current coordinator of the thematic project connected with Auger (the previous projects were coordinated by Escobar), she is monitoring the replacement of the batteries for the Cherenkov tanks. The batteries store the energy that is produced by the solar panels and used by a miniprocessor that detects the signals from cosmic rays and transmits them to the central computer some kilometers away.

"Replacing the two batteries for each of the 1,600 tanks as their service life runs out is a never-ending job, and the support from FAPESP will enable us to do the replacements for the next four years," Chinellato says. Each year an average of 600 batteries must be replaced, or an average of two per day. She says she is monitoring tests in the United States on ten experimental tanks with a new format and new electronics, "also obtained with FAPESP support," she points out. The new tanks use only one light detector instead of the three used in the current tanks.

The present work is relatively simple, given the number of unforeseen events they have already encountered. At the beginning, the Cherenkov tanks did not work for the simple reason that grazing cows took an interest in their new neighbors, the tanks, and some of them began to chew on the data transmission wires. Ricardo Perez, the Argentinian in charge of tank maintenance, used his knowledge as a former mining expert to come up with the idea of a box to protect the wires, and the cows ceased to confound science.

Science on the ground: Patrick Allison, an American, and Xavier Bertou, a Frenchman, install the electronics on a surface detector. At left, one of the cosmic ray photodetectors

"When this project began," Chinellato recalls, "it all seemed like an impossible dream." The world's largest cosmic ray observatory was first planned in 1992 by American physicist James Cronin, a University of Chicago professor and 1980 Nobel Prize winner, and Alan Watson, a Scot from England's University of Leeds. As the need for international cooperation became clear due to the proportions that the original project took on, they invited a few interested colleagues with experience in the field of particle physics for initial talks in June 1995. One of the participants in those talks was Escobar, then a professor at the University of São Paulo (USP).

At a meeting held at UNESCO headquarters in Paris in November 1995, Escobar, Ronald Shellard of the CBPF, Armando Turtelli of Unicamp, and Argentine colleagues Alberto Etchegoyen and Alberto Filevich strenuously supported the idea of the new observatory being built in Argentina. "That was a crucial moment," says Marcelo Leigui, a physicist who took part in that investigation as a postdoctoral researcher at Unicamp and is now a professor at the Federal University of the ABC. "Brazilian participation would have been lower if one of the other two candidates—South Africa or Australia—had been chosen." Brazil's participation, made official on July 17, 2000 at Unicamp, resulted in investments of around US$4 million in the form of equipment purchased from Brazilian manufacturers and the funding of post-graduate research grants and travel expenses.

The job of replacing the 1,600 batteries for the surface detectors began in 2011

Malargüe, a town of 23,000 with two stoplights located 420 kilometers from Mendoza, Argentina's closest urban center with regular airline connections, began to change as work began in mid-1999. Researchers started arriving from the United States, Italy, Germany, Poland, Slovenia, and many other foreign countries. After they got over the initial strangeness, Malargüenses hastened to learn English and began including visits to the observatory's headquarters—a beautiful building with huge expanses of glass instead of walls—on their weekend strolls. Mendoza, known as Argentina's principal wine-producing region, was also advancing in the field of science.

Then began the arrival of trucks—many trucks—carrying equipment. Beginning in early 2001, Alpina, a São Paulo-based company, manufactured and sent the Cherenkov tanks on trips that took at least two weeks and were subject to all manner of unforeseen events, from potholes in narrow roads to highway patrolmen who asked to see what was in the tanks. Rotoplastyc, a company based in the Brazilian state of Rio Grande do Sul, made some of the tanks currently in operation and participated in the development and production of the new-format tanks.

Schwantz, a company based in Indaiatuba in the state of São Paulo, made and sent the corrector lenses for the fluorescence telescopes. The trapezoid-shaped 25-centimeter-high converging lenses, made of German glass, form a corrector ring around the edges of the diaphragm that regulates the entrance of light, like the diaphragm of a camera, and increase the radius of the lens from 85 to 110 centimeters without losing image quality. Equatorial, a company in São José dos Campos in the state of São Paulo, manufactured the prototype for a device 2.5

PHOTOS MIGUEL BOYAYAN

Indonesian physicist Richard Randria analyzes particle showers at the data acquisition center

meters in diameter that automatically regulates the telescope lenses and the shutters that expose the telescope for nighttime observation. Moura, a Recife company, made the batteries for the solar panels on the surface detectors.

Each of the 17 participating countries played a role in sending equipment and researchers, so the observatory has some of the world's best technology. Argentina supplied infrastructure in the form of machines that purify water for the tanks, as well as some of the tanks and batteries for the solar panels that supply the surface detectors, sharing that undertaking with the Mexicans and the Americans. Australia provided the cloud detectors, and France supplied the electronic devices for the surface detectors. The Czechs sent the mirrors for the telescopes, and the Spaniards supplied the solar panels for the tanks. The fluorescent light detectors for the telescopes used Italian cameras and electronic controls made by the English and the Germans.

The readers of this magazine followed the progress of the construction of Pierre Auger. In August 2000, the cover story of *Pesquisa Fapesp*, written by Mariluce Moura, told of the behind-the-scenes negotiations and the start of construction. Another story from April 2002 describes the pace of the work: "At this very moment, in a space which sometimes reminds one of the refinement of a spaceship or the robust workings of a hydroelectric plant, dozens of operators, technicians and researchers are working intensely setting up the cosmic rays measuring equipment." At that time, José Fernando Perez, then scientific director of FAPESP and chairman of the Auger Observatory's finance committee, visited the project in Malargüe. With him was José Roberto Leite, a physicist from the University of São Paulo (USP) and director of the Brazilian Physics Society (SBF), who died unexpectedly the following year.

There were some remarkable aspects about the construction process. First among these is the fact that the data were already being collected as the equipment was being installed. Another is that the physicists and engineers did not hesitate to do any kind of work that was needed. "We have to do whatever is necessary," I was told in 2003 by Frenchman Xavier Bertou, coordinator of scientific operations. Bertou had left Paris the previous year, settled down in Malargüe, and from then never went without his late afternoon gourd of *mate*. He and other physicists, mostly post-docs in their 30s, assembled equipment on the tanks or in the telescope buildings during the day, and at night—often until three in the morning—at the machine shop in the building in town.

"We showed that it is possible to implement a large project under budget," Escobar said in 2007. Total expenditures came to US$54 million, which was US$6 million below budget. How did they do it, when most projects break the budget? By negotiating prices with equipment suppliers and economizing as much as possible. In 2005, when he saw that expenses were piling up, Escobar decided that the members of the Brazilian team would stop taking two flights to get to Pierre Auger and would start going by plane only as far as Buenos Aires. From there they could take a bus and get to Malargüe in 16 hours' travel time. No one objected. One year, Sérgio Carmelo Barroso, a post-doc at Unicamp, had to go to Malargüe ten times to assemble and test equipment. Now a professor at the State University of Southwestern Bahia (UESB), he continues to take part in this work. ■

PROJECTS

1. Study of highest-energy cosmic rays at the Pierre Auger Observatory – nº 2010/07359-6 (2010-2014)
2. Pierre Auger Observatory – nº 1999/05404-3 (2000-2007)

GRANT MECHANISM

1. and 2. Thematic project

COORDINATORS

1. Carola Dobrigkeit Chinellato (Unicamp)
2. Carlos Ourívio Escobar

INVESTMENT

1. R$3,064,952.43
2. R$6,034,341.71

SCIENTIFIC ARTICLE

The Pierre Auger Collaboration. Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects. **Science**. v. 318, n. 5852, p. 938-43, 2007.

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