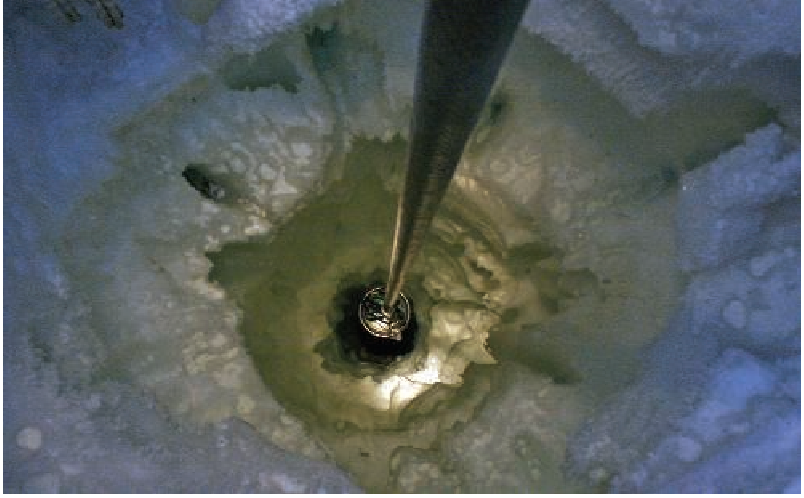

INTRODUCTION

Catching Cosmic Clues

THE AUTHOR HENRY JAMES WROTE THAT "EXPERIENCE IS … A KIND OF HUGE spider-web of the finest silken threads suspended in the chamber of consciousness, and catching every airborne particle in its tissue." Particle astrophysicists are trying to weave their own webs by building vast detectors on Earth and in space that will ensnare cosmic particles and so teach us about the building blocks of the universe.

Thanks to enormous progress in cosmology in recent years, astrophysicists are both pleased and perplexed. On the one hand, they have succeeded in nailing down the universe's mass, geometry, and expansion rate. But on the other, they have discovered that 95% of the stuff of the universe is in two unknown forms that they have named "dark matter" and "dark energy." Only 5% is normal matter: electrons, protons, and neutrons. Pinning down the nature of this missing mass and energy is difficult, because dark matter does not absorb light or interact with normal atoms; the dark energy driving accelerated cosmic expansion is even more intangible. Particle physicists may, however, have the tools to test some ideas. In this special issue devoted to particle astrophysics, a rapidly developing interdisciplinary area, six Perspectives cover not only candidates for dark matter but also the physics of the Big Bang fireball, neutrinos, cosmic rays, and sources of extreme-energy gamma rays such as black holes.

Neutrino physics has leapt ahead in recent years, with measurements of neutrino mass and oscillations between different types, or flavors. The next frontier is neutrino astronomy, capturing neutrinos from sources more distant than the Sun, and vast arrays of detectors are being built under the ice in Antarctica and under the Mediterranean Sea to do this. Neutrinos hardly interact with normal matter at all, but occasionally they do and produce ghostly flashes of light that detectors can catch. If the universe's hidden mass takes the form of other particles, then axions and WIMPs (weakly interacting massive particles) are the prime suspects. Experiments, many hidden below ground to isolate the detectors from other stray particles, have been designed and are being implemented to spot these exotic particles via their recoil off other nuclei. Currently, these detectors are modest in size, but detectors now on the drawing board could weigh as much as a ton.

High-energy particles can also be used for astronomy. Cosmic-ray observatories are nearing the sensitivities required to detect individual sources in the sky, thus testing acceleration physics. Cosmic rays are created by extreme astrophysical sources such as supernova shock waves, gamma-ray bursts, and near black holes. Very-high-energy gamma-ray emission from these sources is already detectable with new telescope arrays and has constrained the physics of particle jets emanating from compact stars and black holes.

Particle astrophysics is an exciting area brimming with promise. As scientists come together to combine their know-how, maybe in the next decade we will find the missing matter, and crown the already remarkable achievements of cosmology.

– JOANNE BAKER

CREDIT: NSF

Particle Astrophysics

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Stalking Discovery From the Infinitesimal to the Infinite

Particle physicists are moving into astrophysics, astronomy, and cosmology; their skills and big-hammer approach could help solve some of the universe's deepest mysteries

STRETCHING FOR HUNDREDS OF KILOMETERS and covered with scrub and prairie grass, the Pampa Amarilla in western Argentina would be an ideal place to graze cattle or film a Western or, on a clear night, gaze at the stars and contemplate one's place in the cosmos. But James Cronin, a particle physicist at the University of Chicago in Illinois, has chosen this unlikely venue to try to solve an enduring mystery of astrophysics.

Cronin and 300 colleagues have come to the foot of the Andes mountains to snare particles from deep space that zing along with energies millions of times higher than particle accelerators have achieved on Earth. If all works as hoped, in a few years researchers will spot the sources from which such cosmic rays emanate. "That's never been done, and that would be a huge breakthrough," says Cronin, who shared the Nobel Prize in physics in 1980 for the discovery of a slight asymmetry between matter and antimatter known as CP violation.

The experiment is no small undertaking. Researchers are carpeting the plain with 1600 detectors spaced 1.5 kilometers apart to sense the avalanche of particles created when a ray crashes into the atmosphere. When it is completed, the Pierre Auger Observatory will cover 3000 square kilometers—five times the area of Chicago. True to his particle physicist's training, Cronin embraces a simple credo: "Just think big."

Cronin is only one of many particle physicists who are turning away from Earth-bound accelerators and toward the heavens. In recent years, researchers have begun explorations at the boundaries between particle physics, astrophysics, and astronomy. They are lurking in caves trying to detect particles of the dark matter that holds the galaxies together; sinking detectors into the ice at the South Pole and the waters of the Mediterranean Sea to sense particles called neutrinos from outer space; building gamma ray telescopes to open new eyes on the cosmos; and tracking stellar explosions known as supernovae to decipher the space-stretching dark energy that is accelerating the expansion of the universe. All these endeavors fall under the nebulous rubric of particle astrophysics, or astroparticle physics.

"It's likely that in the next 10 years, one of these efforts will lead to a major discovery," says Gerard van der Steenhoven, a particle physicist at the National Institute for Nuclear and High Energy Physics in Amsterdam, the Netherlands, who works on a neutrino experiment in the Mediterranean. "That makes it very exciting."

The growth of particle astrophysics is not only rejuvenating particle physics but also changing astrophysics and astronomy. Accustomed to working on immense experiments in huge collaborations, particle physicists bring their skills and strategies to fields in which the experiments are already growing rapidly in size and complexity. "You're bringing in a new culture and a new way of operating at a time when the field [of astronomy and astrophysics] needs it," says Bruce Winstein, a particle physicist at the University of Chicago who now studies the

On the range. Physicists with the Pierre Auger Observatory are covering 3000 square kilometers of Argentine prairie with particle detectors.

CREDIT: PIERRE AUGER OBSERVATORY

afterglow of the big bang, the cosmic microwave background radiation.

But whether particle astrophysics continues to flourish may depend on whether experiments currently in the works deliver any of the hoped-for discoveries. In fact, some say, the future of the field could depend in part on what researchers find at the next great particle collider, currently under construction in Europe.

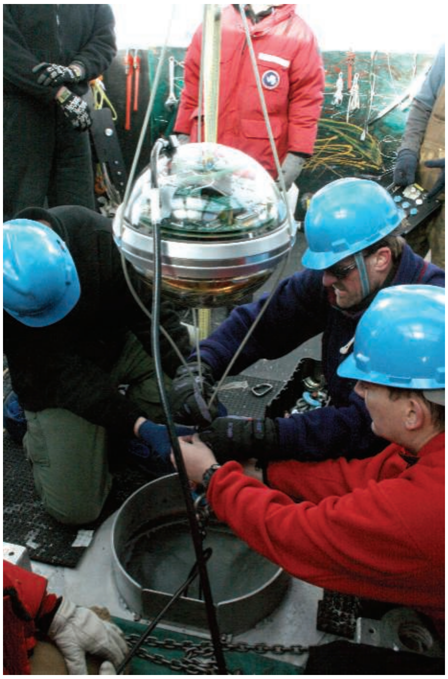
Cosmic connections

In turning toward astrophysics, particle physics is, in a sense, returning to its roots. Physicists spotted the first bit of antimatter—the antielectron, or "positron"—while studying cosmic rays in 1932. In the same way, they discovered the first particle beyond those that make up the everyday matter around us, the muon, a few years later. But particle astrophysics stretches beyond the study of particles from space. It represents a broad movement of particle physicists into fields such as cosmology and astronomy, where they are pursuing the grandest mysteries in the universe, sometimes without a particle in sight.

Most physicists trace the growth of the field to conceptual links between cosmology and particle physics forged in the 1970s and 1980s. For example, theorists realized that the abundance of helium in the universe puts a limit on the number of possible types of neutrinos, wispy particles produced in certain kinds of radioactive decay that interact feebly with everyday matter. (Physicists now know that there are three types of neutrinos.) Others noted that, when mixed into the big bang theory, CP violation might explain why the universe contains so much matter and so little antimatter.

Still others realized that a particle theory might help explain the nature of dark matter, the unidentified stuff whose gravity holds the galaxies together. The standard model of particle physics says that matter is made of particles called quarks and leptons that exchange force particles called bosons. A theory called supersymmetry extends this scheme by positing that every known fundamental particle has a more massive doppelgänger that has yet to be discovered. Some of those particles might just fit the bill for dark matter.

Such connections have blurred the distinction between particle physics and cosmology, says Jonathan Ellis, a theorist at the European particle physics laboratory CERN near Geneva, Switzerland. "I often find it difficult to tell when I'm writing a paper on particle physics and when I'm writing a paper on cosmology, because in my mind the two are inextricably intertwined," he says.



Brrr! Researchers constructing Ice Cube lower a photodetector into the South Pole ice.

CREDIT: JOHN JACOBSEN/NSF

More recently, experimenters have joined the movement to particle astrophysics, inspired by key discoveries made in recent years. Closest to home, the biggest advance in particle physics in the past 2 decades came from researchers studying neutrinos from space with the Super-Kamiokande particle detector in a mine in Japan. In 1998, physicists found that one type of neutrino could transform into another, a phenomenon known as mixing that can occur only if neutrinos have mass. The standard model assumes that neutrinos are massless, so the observation gives researchers their first peek at physics beyond the standard model.

Further afield, scientists studied distant stellar explosions known as type Ia supernovae to trace the history of the expansion of the universe. In 1998, two groups independently reported that the most distant supernovae were even farther away than expected, indicating that the expansion of the universe is accelerating. That stunning observation suggested that some mysterious "dark energy" is stretching the fabric of space.

That revolutionary notion was bolstered in 2003 when researchers working with NASA's Wilkinson Microwave Anisotropy Probe satellite mapped the cosmic microwave background in exquisite detail. Analyzing the tiny temperature differences in the radiation across the sky, they found that the universe consists of roughly 71% dark energy, 24% dark matter, and just 5% ordinary matter.

The very notions of dark energy and dark matter fire the imaginations of researchers who have devoted themselves to asking, "What's it made of?" says Natalie Roe, a particle physicist at Lawrence Berkeley National Laboratory (LBNL) in California. "Having realized that quarks and leptons are only 5% of the universe, I think it's only natural to ask what the other 95% is," she says. "So dark energy and dark matter are natural targets for particle physicists."

Making a move

When explaining their switch into particle astrophysics, researchers cite motives as varied as the particles in the standard model. Most say they were drawn by the intellectual excitement of a young field. "Particle physics was most exciting before the standard model was put in final form and verified," says Steven Weinberg, a theorist at the University of Texas, Austin, who shared the Nobel Prize in physics in 1979 for his work on the standard model and now pursues cosmology. "In cosmology, the questions are more wide open."

LBNL's Roe, who spent a decade studying the properties of quarks to high precision, says she finds it refreshing to work in a field in which researchers generally don't know what to expect from an experiment. "I wanted to look into something that we really didn't understand, where we don't have a standard model," says Roe, who is working on a satellite, the Supernova/Acceleration Probe, that would examine dark energy by measuring thousands of supernovae.

Many researchers say they switched to particle astrophysics in search of a more congenial work environment. Daniel Akerib, a particle physicist at Case Western Reserve University in Cleveland, Ohio, says he moved away from collider experiments, which typically involve hundreds of collaborators, so he could take a more hands-on approach to his work. "I just felt like I was going to spend all my time in meetings and not have any fun," he says. Akerib now works with the Cryogenic Dark Matter Search (CDMS), a small group that runs an extremely sensitive detector in a mine in Minnesota and hopes to spot passing dark-matter particles.

Some physicists have set out in new directions because opportunities in particle physics have dwindled. David Cinabro of Wayne State University in Detroit, Michigan, had been working on an experiment called BTeV that would have run at the Tevatron collider at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois. But in 2005, the U.S. Department of Energy suddenly axed the project. "I was faced with the prospect of starting over no matter what I did," Cinabro says.

Cinabro could have joined one of the experiments at the next great accelerator, the Large Hadron Collider (LHC) at CERN, which is scheduled to turn on late this year. Instead, he joined the Sloan Digital Sky Survey, a novel astronomy effort that uses a 2.5-meter optical telescope on Apache Point, New Mexico, to map everything in one quadrant of the sky. Making the shift wasn't easy, says Cinabro, who is studying supernovae and dark energy. "It's like going back to graduate school, because I'm as ignorant as a first-year graduate student," he says. Still, he says he's happy with his decision.


Homey. Experimenters can take a more hands-on approach with the relatively small CDMS dark-matter detector.

A few researchers say they have pursued particle astrophysics for the sheer adventure of it. "To me it was an opportunity to see Antarctica through the back door and not have to pay for it," quips David Besson of the University of Kansas, Lawrence, who is working on a prototype neutrino detector at the South Pole. In a phone interview from McMurdo Station, Besson says there is something romantic about searching for radio signals produced by cosmic neutrinos crashing into the ice. "It takes you back to that sense of wonder when you were 5 years old and you'd look up and see the stars," he says. "Not that you could do that where I grew up in New Jersey."

Rearranging the furniture

As interest in particle astrophysics has grown, so has funding for such research. For example, in 2000, the U.S. National Science Foundation (NSF) instituted a program in particle and nuclear astrophysics, which now has a $16 million annual budget. And since 1994, the United Kingdom has funded particle physics, particle astrophysics, and astronomy jointly out of its Particle Physics and Astronomy Research Council. But even as the growth of particle astrophysics is expanding the boundaries of particle physics, it is also changing the practice of astronomy and astrophysics.

Most obviously, particle physicists bring with them technologies that are opening new avenues of inquiry. For example, NASA's Gamma-Ray Large Area Space Telescope (GLAST), which is scheduled for launch this October, will provide astronomers with an unparalleled view of the universe as seen in very-high-energy photons. But the "camera" that will detect the gamma rays is a particle detector built at the Stanford Linear Accelerator Center (SLAC) in Menlo Park, California. "In the end, what you need is the best equipment you can get to solve the problem. And if it comes from some other field, why not?" says SLAC's Eduardo do Couto e Silva.

Particle physicists have also introduced a different style of collaboration to astronomy and astrophysics, as exemplified by the Sloan survey. When sharing a telescope, astronomers traditionally allot observers time to use the instrument in turn. In contrast, Sloan researchers pull together to crank out a steady stream of data in a general format, so that collaborators can analyze the data any way they please, just as in a collider experiment. In essence, the Sloan telescope produces astronomical data just as a factory might produce brake pads.

Perhaps most important, particle physicists have appetites for huge projects that push the limits of technology, organization, and funding. "These are not people who are afraid to ask for big things, and they're used to people saying yes," says Michael Turner, a cosmologist at the University of Chicago who served as assistant director of NSF's mathematics and physical sciences directorate from October 2003 until April 2006. As particle physicists enter astrophysics and astronomy, their habit of "thinking big" is accelerating the natural growth of the size of projects, Turner says.

But even as particle astrophysics blossoms, some researchers worry about its future. Steven Ritz, a particle physicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and project scientist for GLAST, fears that the rise of particle astrophysics could undermine accelerator-based research. "Sometimes the movement is interpreted to mean that there's no need to build accelerators anymore, that you can do it all from space," he says, "and that's just not right." Even so, the number of colliders is falling, especially in the United States. SLAC will shutter its PEP-II collider in 2008, and a year later Fermilab will unplug the Tevatron, leaving the United States with no colliders for particle physics.

Others say the growth of particle astrophysics will likely slow as the size and expense of projects balloons. "It will soon hit a wall that particle physics hit some time ago, and that is the $1 billion experiment," says Francis Halzen, a particle theorist–turned-experimenter at the University of Wisconsin, Madison. Halzen's own experiment, Ice Cube, exemplifies the growth of projects in particle astrophysics. A mammoth array of photodetectors being embedded between 1.5 and 2.5 kilometers deep in the South Pole ice, Ice Cube will detect light produced when ultrahigh-energy neutrinos crash into the ice. Scheduled for completion in 2011, the experiment will cost $271 million and involve 400 researchers.

Most of all, the future of particle astrophysics depends on what experiments currently in the works might find. Roger Blandford, a theoretical astrophysicist at Stanford University in Palo Alto, California, says the first big test will come in the search for dark matter. "Our working hypothesis is that dark matter comprises supersymmetric particles," he says. "We could be terribly wrong." Given that hypothesis, the prospects for the searches would brighten if the LHC discovers supersymmetric particles—and dim if it doesn't.

For the moment, researchers working in particle astrophysics are happy just to participate in such a young and dynamic field. Promises of momentous discoveries abound. Expectations are sky high.

–ADRIAN CHO

CREDIT: REIDAR HAHN/FERMILAB VISUAL MEDIA SERVICES

PERSPECTIVE

Quarks and the Cosmos

Michael S. Turner

Cosmology is in the midst of a period of revolutionary discovery, propelled by bold ideas from particle physics and by technological advances from gigapixel charge-coupled device cameras to peta-scale computing. The basic features of the universe have now been determined: It is 13.7 billion years old, spatially flat, and expanding at an accelerating rate; it is composed of atoms (4%), exotic dark matter (20%), and dark energy (76%); and there is evidence that galaxies and other structures were seeded by quantum fluctuations. Although we know much about the universe, we understand far less. Poised to dramatically advance our understanding of both the universe and the laws that govern it, cosmology is on the verge of a golden age.

The universe is often just beyond our grasp, and progress in cosmology usually comes only with advances in technology or with powerful new ideas. In the 1920s, Hubble used the new 100-inch Hooker telescope on Mount Wilson to discover the expansion of the universe, and Einstein's young theory of general relativity provided the mathematics needed to understand our Big Bang beginning. Only with the advent of the 200-inch Hale telescope on Mount Palomar in the 1960s did astronomers push to the edge of the observable universe, and radio technology made possible the discovery of the microwave echo of the Big Bang in 1964 by Arno Penzias and Robert Wilson, revealing that, at its creation, the universe was hot as well as dense.

Cosmology slipped into the doldrums in the 1970s and was aptly described by Sandage as the search for two numbers: the expansion rate H_0 and the deceleration parameter q_0 (*1*). Although the basics of the hot Big Bang model were in place, including the picture of how structure in the universe formed by gravity amplifying small variations in the matter density into galaxies, clusters of galaxies, and superclusters, there was no evidence for the tiny seed inhomogeneities that were required to form structure or hints as to their origin. Moreover, our understanding of cosmology hit a brick wall at 10^{-5} s, which blocked connecting with its earliest moments and a deeper understanding of the Big Bang. Because of missing physics, the early universe was thought to be a confusing sea of overlapping protons, neutrons, and other elementary particles.

Today, cosmology is in the midst of a revolutionary period of discovery. In the past 8 years, the field has twice captured *Science*'s Breakthrough of the Year: for the discovery of the acceleration of the expansion of the universe in 1998 (*2*) and for the concordance cosmological model in 2003 (*3*). The revolution traces its beginnings to the 1980s with the arrival of powerful new ideas and advances in technology: from the discovery of quarks and the introduction of charge-coupled devices to space-based telescopes and string theory.

New ideas from particle physics changed the language as well as the conversation in cosmology. Physically based quantities climbed to the top of the list of wanted parameters: the temperature, spectrum, and anisotropy of the cosmic microwave background (CMB); the shape of the universe; the composition of the universe; the large-scale distribution of matter today; and the spectrum of seed inhomogeneities.

By using bigger telescopes, better detectors, and faster computers, astronomers and physicists have determined all of these parameters and more to percent-level precision, turning an oxymoron—precision cosmology—into reality. And in most cases, it is not just one measurement but an interlocking web of complementary determinations that pin down the parameters, strengthening the framework and changing the tenor of cosmology. Cosmology is no longer the field described by the Russian physicist Lev Landau who said, "Cosmologists are often in error, but never in doubt."

This then is our universe: On the whole, it is spatially flat and 13.7 billion years old, both of which are known to 1% precision; it is expanding at a rate of 70 ± 2 km/s per megaparsec, and the expansion is speeding up; and it is composed of 24 ± 4% matter and 76 ± 4% dark energy, with 4.2 ± 0.5% of the matter in the form of atoms, between 0.1 and 1% in the form of neutrinos, and with the bulk of the matter dark and as yet unidentified (*4*). Stars, the only constituent of Sandage's universe, account for less than 1% of the total composition. The microwave background temperature has been measured to four significant figures, 2.725 ± 0.001 K (*5*), and its tiny variations (about 0.001%) across the sky have been mapped with a resolution of better than 0.1° (*6*).

The discovery of quarks (the constituents of neutrons and protons) and the realization that they interact weakly when close together knocked down the brick wall and opened the door to understanding the nature of the very early universe: It was a hot soup of quarks and other elementary particles and almost as easy to describe as the chemists' perfect gas. Thinking of the early universe as quark soup changed the big questions: Where is the antimatter? What is the origin of the seed inhomogeneity? Why is the universe so smooth, nearly flat, and very old? Where did the heat of the Big Bang—today existing in the billion CMB photons per atom—come from? What powered the Big Bang?

Speculations about the earliest moments of creation and possible answers to all the big questions, based on bold ideas about how the fundamental particles and forces of nature are unified, burst forth. Many ideas have been influential (for example, how neutrino mass and "charge-parity" violation can explain the absence of antimatter and the few atoms per billion photons in the universe today), but two ideas have been central to the current revolution: dark matter as a new form of matter, and inflation as a dynamical explanation for the most salient features of the universe.

As cosmological observations were establishing that there was insufficient atomic matter to account for the vast amounts of dark matter needed to hold together cosmic structures from galaxies to superclusters, particle physics came forward with three well-motivated candidates for dark matter. The fate of the first candidate, the neutrino, turned on neutrino mass; we now know that neutrinos have mass and are part of the dark matter, but only a tiny part of it, accounting for less than 1%. Hopes are now pinned on two still-to-be-discovered particles: (i) the neutralino, which is expected to have a mass of about 100 times that of the proton and to be the lightest of a new class of particles predicted by string theory, and (ii) the axion, a particle that is expected to be a trillion times less massive than the electron (*7*).

The central tenet of inflation is a very early burst of accelerated expansion driven by yet-to-be-understood physics involving a new scalar field called the inflaton. This rapid expansion led to a smooth, flat, and hot universe (the heat produced by the conversion of the inflaton's energy into particles), and quantum fluctuations, blown up from subatomic scales to astronomical scales, created the density inhomogeneities that seeded all cosmic structure (*8*).

Taken together, inflation and dark matter led to the cold dark matter (CDM) theory of structure formation (cold refers to the fact that the dark matter particles such as the axion and neutralino move slowly, which leads to predictions that do not depend on the mass of the dark matter particle) (*9*). CDM describes in detail how cosmic structure formed and how the bright side of the universe came to be, and it has stimulated the observations (made possible by new technology) that have now filled in the story line of the formation and evolution of galaxies and large-scale structure, from shortly after the birth of the first stars (less than a billion years after the Big Bang) until today.

NASA's Cosmic Background Explorer (COBE) satellite, which first detected the tiny variations in the CMB intensity across the sky (anisotropy) in 1992 (*10*), confirmed the existence of the underlying matter inhomongeneity that seeded structure and began a new era in

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cosmology. Encoded in the CMB anisotropy is information about the past, present, and future of the universe (Fig. 1). (In 2006, John Mather and George Smoot received the Nobel Prize in Physics for their work on COBE.)

COBE was followed up by NASA's Wilkinson Microwave Anisotropy Probe (WMAP) and a host of ground- and balloon-based CMB experiments. The results from these higher-resolution and higher-precision measurements, together with maps of the large-scale structure of the universe made by the Sloan Digital Sky Survey and Two-Degree Field project, have precisely determined cosmological parameters, established the basic correctness of the CDM paradigm, and provided strong support for the ideas of particle dark matter and inflation (*4*).

Inflation and particle dark matter were new ideas by design; dark energy, on the other hand, came as a surprise. The quest for Sandage's second number, q_0, took an unexpected turn in 1998. Armed with new technology and a better standard candle to determine cosmic distances (type Ia supernovae, the nuclear explosions associated with white dwarf stars pushed over the Chandraskehar mass limit by accretion from a companion), two teams presented evidence that the expansion of the universe is speeding up, not slowing down (*11*, *12*): that is, q_0, so carefully defined to be positive, is actually negative!

Although the mystery of cosmic acceleration surely ranks as one of the most profound puzzles in all of science today, it was also the missing piece that pulled the current picture together. Toward the end of 1990s, the inflation/CDM paradigm was working well except for one "small" detail: There was growing evidence for both a flat, critical-density universe and for a matter density that was only 30% of the critical density. Where was the other 70% of the critical density? Cosmic acceleration solved the problem: The observed cosmic speed up indicated the existence of a very smooth and diffuse form of very elastic energy (now referred to as dark energy), which accounts for the missing 70%. When the discovery of cosmic acceleration came, the current concordance model, as absurd as it seems, was quickly embraced. [In fact, two theoretical papers anticipated this solution a few years before the discovery (*13*, *14*).]

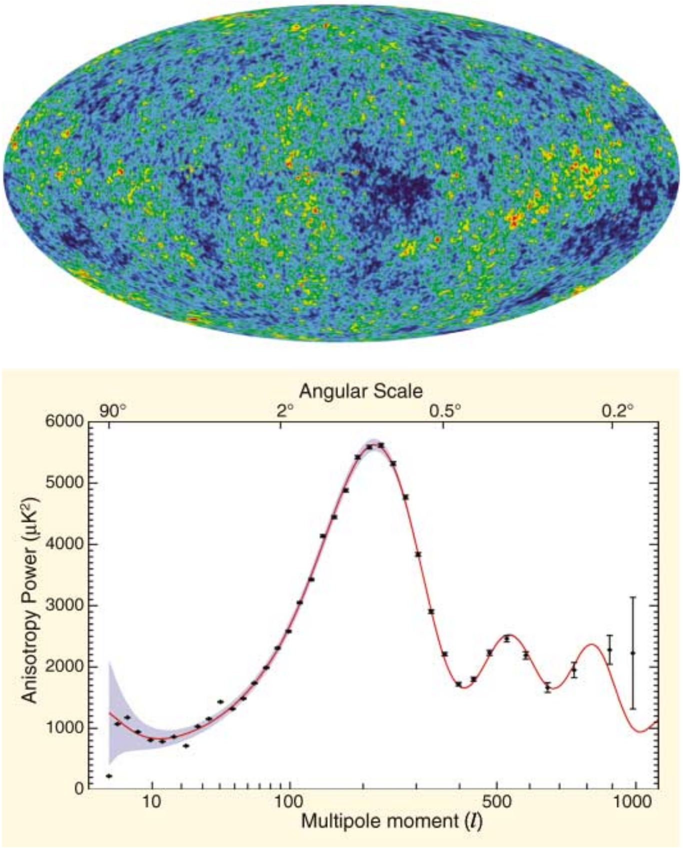

Fig. 1. The CMB seen by WMAP. (**Top**) The hot (red) and cold (blue) spots on microwave sky, as measured by WMAP, map out the tiny inhomogeneities in the distribution of matter when the universe was about 400,000 years old; the full range of the variations is ±200 μK, corresponding to variations of about 0.01% in the matter density. (**Bottom**) The spherical-harmonic multipole content of the anisotropy reveals the underlying mathematical structure that has been used to determine cosmological parameters and to provide for cosmic inflation. The points and their error bars indicate the WMAP measurements and their estimated errors, and the solid curve is the prediction of the concordance cosmological model. The shaded area indicates the "cosmic variance" interval for each multipole, which fundamentally limits the precision with which the underlying theory can be tested. (Cosmic variance arises because the underlying multipole distribution is being estimated by measuring the $2l + 1$ multipole moments that can be determined for a given l.) [Image: NASA/WMAP Science Team]

Within general relativity, dark energy can account for cosmic acceleration because Einstein's theory predicts that a substance whose pressure is more negative than one-third of its energy density has repulsive gravity. Ideas about what dark energy is range from the energy of the quantum vacuum to the existence of another new scalar field (called quintessence and possibly related to the inflaton) to the influence of unseen additional spatial dimensions predicted by string theory (*15*). The most interesting possibility of all is the absence of dark energy, with cosmic acceleration being explained by a new aspect of gravity, one not accounted for by general relativity (*16*, *17*).

The roots of the dark-energy puzzle extend back to the birth of quantum mechanics and Einstein's famous fudge factor. According to quantum mechanics, the vacuum should be filled with a sea of "virtual" particles whose existence is allowed by the uncertainty principle. The effects of these virtual particles are very real (they shift atomic lines and elementary particle masses) and have been measured. With a bulk pressure equal to the negative of its energy density and mathematically equivalent to Einstein's cosmological constant, quantum vacuum energy would seem to be the obvious explanation for cosmic acceleration. However, there is one small problem: When theorists try to calculate how much quantum nothingness weighs, they get a number that is absurdly large (one that is actually infinite). The so-called cosmological constant problem (*18*), which has been around for more than 30 years, can no longer be ignored because it is now tied to understanding why the expansion of the universe is speeding up.

Today, we know much about the universe—its shape, age, composition, evidence for an inflationary beginning, and timeline from quark soup through the formation of large-scale structure (Fig. 2)—but we understand little about the universe with its odd mixture of atoms, dark matter, and dark energy. We do not know what the bulk of the dark matter is, why the expansion is accelerating today, or if the universe actually underwent an early burst of inflationary expansion and, if so, what caused it. To put a new twist on Landau's words, cosmologists today are rarely in error but are often in doubt.

With the new accelerators, telescopes, and experiments on the horizon, there is certainly much more to come in cosmology over the next 15 years. The neutralino could be produced at Fermilab's Tevatron or the Large Hadron Collider at CERN, or the neutralinos or axions that hold together the Milky Way could be detected by an ultrasensitive detector (*7*). A new generation of CMB experiments zeroing in on the polarization could reveal the third and most definitive signature of inflation (i.e., the gravitational waves that arise because of quantum fluctuations in the metric of spacetime) and pin down when inflation occurred. A dark-energy space telescope could shed light on why the universe is accelerating.

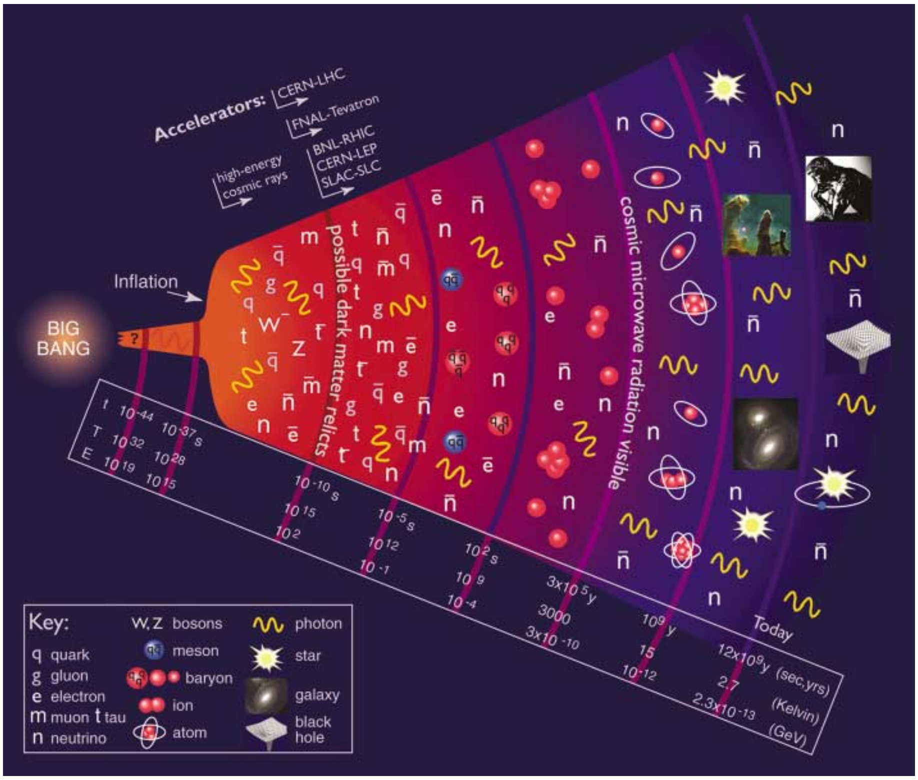

Fig. 2. The Big Bang timeline, from inflation to quark soup to the birth of the light nuclei to the formation of atoms and ultimately of galaxies and other gravitationally bound structures. [Image: Particle Data Group/Lawrence Berkeley National Laboratory/U.S. Department of Energy/NSF]

Because the scientific agendas of cosmology and particle physics have converged, as we deepen our understanding of the universe, we will advance our understanding of the fundamental laws that govern it as well. Nowhere in particle physics are the stakes higher than for string theory. If string theory is to live up to its billing as "the theory of everything" rather than, as some say, a theory of nothing, it needs a home run. Because most of its current predictions exceed the reach of terrestrial laboratories, many string theorists are pinning their hopes on a cosmological home run, such as a fundamental understanding of inflation (or a more attractive alternative), a solution to the puzzle of cosmic acceleration, or insight into the nature of the Big Bang itself.

Beyond the next 15 years, the future of cosmology is less clear. The universe could, as it has before, slip beyond our reach. Just as particle physicists were simultaneously blessed and cursed with the success of their standard model, we could find ourselves with even more precision but no more understanding. Nevertheless, I am bullish and predict that this longest boom in cosmology will ultimately earn the status of a golden age, for dramatically advancing the understanding of both quarks and the cosmos.

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10.1126/science.1136276

PERSPECTIVE

Particle Dark Matter in the Universe: At the Brink of Discovery?

Bernard Sadoulet

The nature of dark matter is one of the central problems of cosmology, particle physics, and gravity. It may be made of still unknown particles produced in the early universe. Much progress has been made in attempts to detect these particles and in the development of the required experimental techniques. Results from direct searches, the Large Hadron Collider, and the Gamma-ray Large Area Space Telescope offer promising opportunities within the next decade to find the missing dark matter.

The past decade of precision cosmological observations has led us to a surprising model of the universe (*1*, *2*): Ordinary matter (baryons and electrons) represents only 5% of its energy density; the rest does not interact with photons and constitutes the "dark side" of the universe. Some 25% of the total energy density clumps under the influence of gravity, forming the mysterious dark matter whose existence we infer from observations of galaxies and the cosmic microwave background radiation (CMBR). Moreover, 70% of the total energy density appears to be in the form of an even more mysterious dark energy, with negative pressure, which accelerates the expansion of the universe. However, we do not know the nature of this dark matter and we know even less about this dark energy.

We do know that dark matter is not made of baryons (protons and neutrons), because the baryon density, inferred from the primordial abundance of light elements or the CMBR, is much lower than the total matter density. This conclusion has been confirmed by unsuccessful attempts to observe dark baryons, such as those in the form of planetary-sized massive compact halo objects (MACHOs). Light massive neutrinos are also ruled out: Cosmology constrains the sum of their masses to be less than half an electron volt (*1*, *2*). Most evidence now points to "cold" dark matter (i.e., particles that are nonrelativistic at the time of galaxy formation). The combination of cold dark

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matter with inflation and dark energy leads to an impressive account of how structure formed in the universe, in accordance with most observations.

From the point of view of particle physics and gravity, dark matter may be the most compelling evidence that there is physics "beyond the standard model." We know, for instance, that despite its success in describing strong interactions, quantum chromodynamics violates charge-parity symmetry, in strong disagreement with experiment. The most elegant method to deal with this flaw leads to the prediction of a new particle, the axion, that may explain the dark matter. Axions from the halo of our Galaxy can be detected by scattering off the virtual photons of a magnetic field. They would produce real photons in the frequency range 100 MHz to 100 GHz, depending on the axion mass. By arranging for these photons to excite a resonance in a finely tuned radiofrequency cavity kept at low temperature, we can bring the expected feeble signal above the noise level of the best modern amplifiers. With this method, the ADMX (Axion Dark Matter Experiment) group is reaching cosmologically interesting limits (*3*) in the mass range of 2 to 2.2 μeV/c^2 (where c is the speed of light) for one generic class ("KSVZ") of axion models. During the next 2 years, the group plans to explore the 10^{-6} to 10^{-5} eV/c^2 interval and then increase the sensitivity of its experiment to include other axion types (e.g., "DFSZ") with superconducting quantum interference device–based radio frequency amplifiers. However, higher mass ranges (up to 10^{-3} eV) may be difficult to probe with this method.

Weakly interactive massive particles (WIMPs) form another candidate class. They arise naturally if we assume that the cold dark matter is made of massive particles that were once in thermal equilibrium with ordinary matter in the early universe. As the universe expanded and cooled, they might have dropped out of equilibrium when they were nonrelativistic. In this case their present density would be inversely proportional to their interaction rate. To explain dark matter, we need interaction rates typical of the electroweak scale, hence their name. Inversely, we know that the very successful electroweak unification is unstable. To stabilize it, it is necessary to introduce new physics at the same scale, which could be supersymmetry, compact or warped additional dimensions, or the "little Higgs." The least massive of the new particles introduced is usually stable and interacts at the level needed to form dark matter. For very different reasons, particle physics and cosmology then lead to the same concept of WIMPs.

It is therefore attractive to detect WIMPs from the halo of our Galaxy, for example, by elastic scattering on a suitable target. The experimental challenges appear daunting. Expected rates are on the order of one event per kilogram of target per week or per month, much smaller than radioactivity rates in the purest materials. Moreover, the typical recoil energy of 15 keV of scattering on nuclei is very small. Extremely sensitive detector technologies are therefore required with the ability to actively reject the radioactive backgrounds. If the ambient fast neutron level can be sufficiently reduced (by moderation by hydrogenated material and a location deep enough underground), WIMPs are the only known potential source of nuclear recoil events. We can then use unique characteristics of nuclear recoils in terms of pulse shape of the signal or ratios of ionization, scintillation, or total energy deposition to reject electron recoils due to gamma-ray or electron interactions. The ultimate goal is to construct a background-free experiment where this rejection occurs event by event.

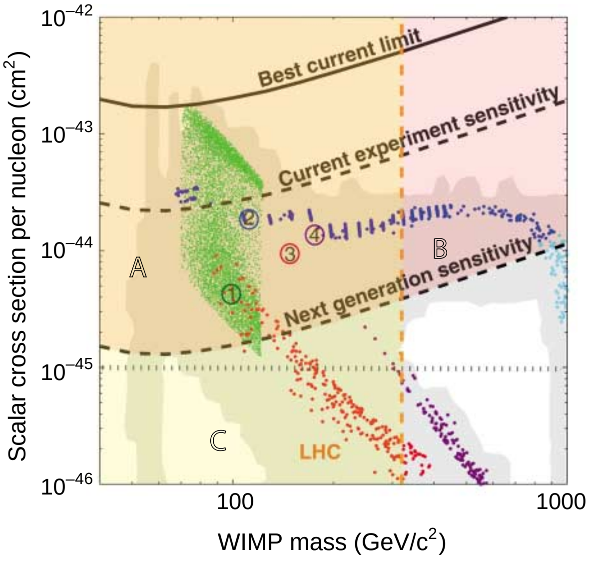

Fig. 1. Sensitivity of current and future experiments to scalar WIMP interactions (*7*). The upper curve is the present best limit (CDMS 2005). The dashed curves show expected sensitivities of the current generation of experiments and of the next generation. The shaded region is the general region of supersymmetry (*8*) compatible with observations. The benchmarks of (*6*) are identified by number. Colored points denote generic regions of supersymmetric models (green, bulk region; blue and cyan, focus point region; purple, co-annihilation; red, funnel). The Large Hadron Collider (LHC) will have difficulty reaching WIMP masses above 350 GeV.

How would we know that we are observing WIMPs? In addition to being nuclear recoils, WIMP interactions should be single scatters uniformly distributed throughout the detector volume. In contrast, neutrons and gamma rays scatter every few centimeters for dense detectors. Eventually, linkage to the galaxy can be established through recoil directionality (which requires low-density media because the recoil length is about 10^{-5} g/cm^2, or a few hundred angstroms in germanium) and yearly modulation of the signal (a few-percent effect that requires several thousands of events to establish). Here, we review the techniques proposed to achieve these goals [see also (*4*, *5*)].

A first generation of experiments attempted to use germanium at 77 K and sodium iodide (NaI), but their sensitivity was limited by the lack of active background rejection. The DAMA (Dark Matter) group claims to have observed WIMPs on NaI through annual modulation. However, their assertion suffers from internal inconsistencies and has not been independently confirmed.

Phonon-mediated (sometimes called "cryogenic") detectors played a pioneering role in demonstrating nearly background-free performance with target masses of around 1 kg. The EDELWEISS (Experience pour Detecter les WIMPs en Site Souterrain) and CRESST (Cryogenic Rare Event Search with Superconducting Thermometers) experiments sense phonons produced in the interactions in the form of a temperature increase measured by highly sensitive thermistors, whereas the CDMS (Cryogenic Dark Matter Search) experiments detect the athermal phonons through their breaking of Cooper pairs in superconducting films covering the surface. These experiments operate at temperatures of 10 to 40 mK so that these athermal phonons are not overwhelmed by thermally excited ones. In addition to their high energy sensitivity, phonon-mediated detectors can discriminate against electron recoils by combining their phonon measurement with ionization measurement at low electric field or with scintillation. Because of the additional information provided by athermal phonons and the additional rejection they provide against surface events, the CDMS II experiment is roughly a factor of 10 more sensitive than any other in the world and begins to enter into the cross section expected for supersymmetry (Fig. 1). In combination with the limits from high-energy solar neutrinos, these results increase the tension with the DAMA claim. Phonon-mediated experiments now in operation use target masses of around 5 kg, with sensitivities 10 times the present limit. New proposals such as SuperCDMS are aiming for 25-kg targets, which should be able to reach 10^{-45} cm^2 per nucleon for a WIMP mass of 60 GeV/c^2, in the next 6 years. The challenge will be to extrapolate these methods to the 1000-kg scale.

Substantial progress has also been made with the use of noble liquids (Ne, Ar, Xe). By comparing scintillation and ionization, it is possible to distinguish nuclear and electron recoils. This requires the amplification of the ionization signal, e.g., by extracting the electrons from the liquid into the gas and having them scintillate in a high–

electric field region. This amplification has now been achieved in three different experiments—ZEPLIN II (Zoned Proportional Scintillation in Liquid Noble Gases) and XENON 10 in Xe, and WARP (WIMP Argon Program) in Ar. Another breakthrough recently occurred when it was realized that for Ne and Ar the pulse shape of nuclear recoils drastically differs from that of an electron recoil. It is then possible to consider a scintillation-only scheme: A sphere is filled with a noble liquid, and the sphere's inner surface is covered with a high density of photomultipliers. A fiducial region protected from external radioactivity can then be defined in the center of the detector, and pulse shape discrimination allows the recognition of nuclear recoils. This scheme is used by the CLEAN (Cryogenic Low-Energy Astrophysics with Neon, which may initially use argon) and XMASS (Xenon Neutrino Mass Detector) proposals. These techniques may gracefully scale to high target masses. However, it remains to be seen what thresholds can be reached.

Gaseous detectors are another option. At low pressure, or higher pressure with sufficiently dense pixels, it should be possible to detect the direction of the recoil. Typically these devices drift charges over long drift length in a time projection chamber. Carrier diffusion must be limited, for example, by a negative ion drift technique. The DRIFT (Directional Recoil Identification from Tracks) group is currently testing underground a cubic-meter prototype at 40 torr (167 g of CS_2). But it is clear that to reach the hundreds of kilograms that are needed, very large chambers of several thousand cubic meters will be needed with some 10^9 pixels, 1 mm on the side.

Metastable systems may enable the construction of detectors that are sensitive to the high energy density created by nuclear recoils and not to photons. One may use Freon droplets [PICASSO (Project in Canada to Search for Supersymmetric Objects), SIMPLE (Superheated Instrument for Massive Particle Experiments)] or a very stable bubble chamber [COUPP (Chicagoland Observatory for Underground Particle Physics)]. Unfortunately, such detectors are also sensitive to alpha interactions and any nucleation agent such as dust. With sufficient purity, it should be possible to produce inexpensive large-mass detectors that are sensitive only to WIMPs. Although these detectors may reach interesting upper limits quickly, they may lack the redundancy needed to substantiate a signal.

These searches complement other experiments, in particular at the Large Hadron Collider (LHC) scheduled to start operation in 2008. Note that the detection of missing energy events at the LHC would not be a sufficient proof that the nature of dark matter has been deciphered. Particles produced at the LHC might be unstable and decay into superWIMPs (such as gravitinos) impossible to detect directly. The simultaneous detection of WIMPs in dark matter experiments and at the LHC (Fig. 1) would open a very rich field of investigation (*6*), but there are scenarios where WIMPs are accessible to only one technique. On a similar time scale, the GLAST (Gamma-ray Large Area Space Telescope) satellite may detect gamma-ray emission from WIMP annihilation in galaxies (possibly two to five identifications within 5 years). Emission from WIMP annihilation is also expected from the galactic center, but the interpretation of a signal may not be unique.

Deciphering the nature of the dark matter in the universe is important not only for astrophysics and cosmology but also for particle physics and gravity. The most unambiguous results may come from the direct detection of halo dark matter in the laboratory. For axions and WIMPs, current technologies are reaching sensitivity levels of cosmological interest and a number of novel detection schemes are in development. The roadmap for WIMP searches appears to be clear: It is important to increase the target mass rapidly while maintaining zero background. This could be achieved by a combination of searches based on the demonstrated phonon-mediated sensors and on promising new technologies such as noble liquids, with several experiments cross-checking each other. The region of 10^{-45} cm^2 per nucleon appears particularly interesting and reachable within the next years, by which time the LHC will test supersymmetry or additional dimensions, and GLAST will fly. If we are lucky, we may indeed be at the brink of a discovery. If such a discovery occurs, by linking the recoil directions to the galaxy, we may even confirm that the observed events are indeed due to dark matter.

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10.1126/science.1136639

PERSPECTIVE

Neutrino Astrophysics: A New Tool for Exploring the Universe

Eli Waxman

In the past four decades a new type of astronomy has emerged, where instead of looking up into the sky, "telescopes" are buried miles underground or deep under water or ice and search not for photons (that is, light), but rather for particles called neutrinos. Neutrinos are nearly massless particles that interact very weakly with matter. The detection of neutrinos emitted by the Sun and by a nearby supernova provided direct tests of the theory of stellar evolution and led to modifications of the standard model describing the properties of elementary particles. At present, several very large neutrino detectors are being constructed, aiming at the detection of the most powerful sources of energy and particles in the universe. The hope is that the detection of neutrinos from these sources, which are extra-Galactic and are most likely powered by mass accretion onto black holes, will not only allow study of the sources, but, much like solar neutrinos, will also provide new information about fundamental properties of matter.

Neutrino astronomy was initiated as an attempt to provide a direct experimental test for the theory of stellar evolution (*1*). According to this theory, the Sun is powered by the nuclear fusion of hydrogen into helium, which takes place deep in the solar interior. The mass of four H atoms is larger than that of the He atom into which they fuse. The excess mass *m* is converted to energy, according to $E = mc^2$ (*c* is the speed of light), which keeps the Sun shining. It was suggested in the mid-1960s that one could test this model by searching for neutrinos, which were predicted to be emitted by the fusion process. Unlike photons that are emitted from the Sun's surface, the weak interaction of neutrinos with matter allows them to escape from the Sun's core and directly reach detectors on Earth.

The weak interaction of neutrinos with matter also implies that they are very difficult to detect, requiring the construction of detectors with several kilotons of detecting medium. Although the probability that a neutrino passing through kilotons of matter would interact within the detector, or be "captured," is very small, the large flux of neutrinos from the Sun, some 100 billion neutrinos per square centimeter per second, allows hundreds of them to be detected every year. In addition to being very massive, all detectors are also buried deep underground. At the surface of Earth there is a large flux of high-

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energy particles. Such particles are produced mainly by the interaction of cosmic-rays, high-energy particles produced in space, with the atmosphere. Penetration of high-energy particles into the detector may lead to interactions that would mimic neutrino interactions. Burial of the detector deep underground suppresses this background, because only neutrinos can penetrate deep enough into Earth to reach the detector.

The detection of solar neutrinos was an impressive confirmation of the hypothesis of a nuclear fusion origin of stellar energy. However, it also posed a challenge: The measured neutrino flux was roughly one-half that predicted by theory. Shortly after this discrepancy was first reported in 1968, it was suggested to be due to shortcomings of the standard model describing the properties of elementary particles (*2*). Neutrinos come in three types, or "flavors": electron-type (ν_e), muon-type (ν_μ), and tau-type (ν_τ). It was proposed that about half of the neutrinos, which are produced in the Sun by nuclear fusion and are all of electron-type, change their flavor to ν_μ or ν_τ as they propagate to Earth. Such flavor conversion, commonly termed "oscillation," was not expected according to the standard model and would explain why neutrino detectors sensitive to ν_e only would miss about half of the solar neutrino flux.

The oscillation explanation was confirmed in 2001 with the detection of the "missing" ν_e flux in the form of ν_μ and ν_τ flux by an experiment sensitive to all flavors (*3*). Independent evidence for neutrino oscillations came from measurements of atmospheric neutrinos, produced by cosmic-ray interactions in the atmosphere, which indicate conversion of ν_μ to ν_τ (*3*). Neutrino oscillations are the first, and so far only, experimental phenomenon not accounted for by the standard model. It is most naturally explained by a model in which three neutrinos with different masses exist—say, ν_1, ν_2, and ν_3 with masses m_1, m_2, and m_3, respectively—and in which neutrinos of different flavors are in fact composed of different mixtures of ν_1, ν_2, and ν_3. ν_e, for example, is a roughly equal mixture of ν_1 and ν_2 with little (if any) contribution of ν_3.

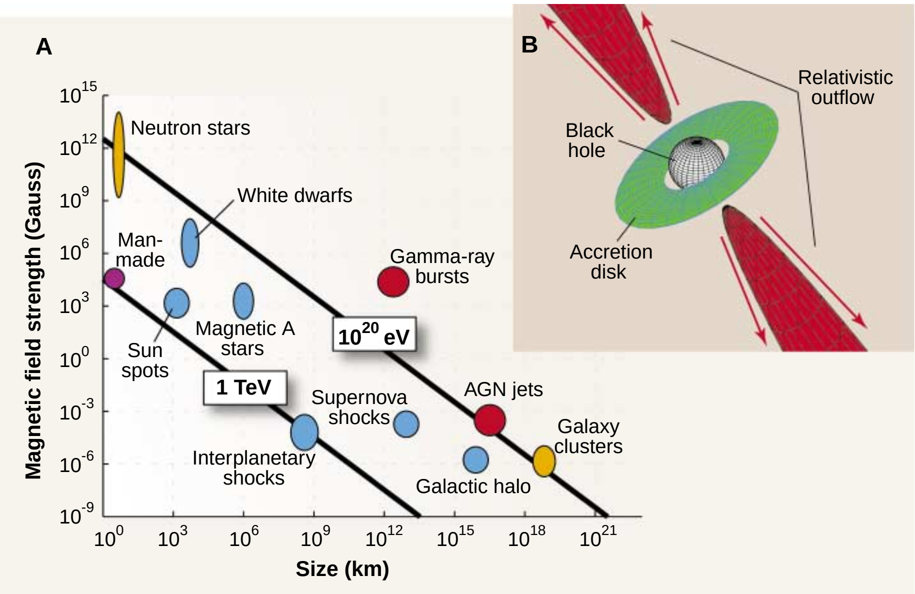

Fig. 1. (**A**) Charged particles are confined to their astrophysical accelerators by magnetic fields. Magnetic confinement requires the product of field strength and accelerator size to exceed a value, which increases with particle energy. The figure shows the size and magnetic field strength of possible sites of particle acceleration. (The magnetic field is measured in Gauss units, where the Earth's magnetic field is ~1 G.) Proton acceleration to 1 TeV or 10^{20} eV is possible only for sources lying above the appropriately marked lines. This is a necessary, but not sufficient, requirement: Proton acceleration to 10^{20} eV is impossible in galaxy clusters (because the acceleration time in these objects is larger than the age of the universe) and unlikely in highly magnetized neutron stars (due to severe energy losses). The characteristics of terrestrial man-made accelerators, which are planned to reach ~ 1 TeV, are shown for comparison. (**B**) GRBs and AGN are believed to be powered by black holes. The accretion of mass onto the black hole, through an accretion disk, releases large amounts of gravitational energy. If the black hole is rotating rapidly, the rotational energy may also be released by slowing the black hole through interaction with the disk. The energy released drives a jetlike relativistic outflow. The observed radiation is produced as part of the energy carried by the jets is converted, at a large distance from the central black hole, to electromagnetic radiation. GRBs are believed to be powered by ~1–solar mass black holes with jets extending to distances larger than the size of the solar system, producing short (typically 1- to 100-s-long) flashes of luminosity exceeding that of the Sun by 19 orders of magnitude. AGN are powered by million– to billion–solar mass black holes residing at the centers of distant galaxies, with jets extending to distances larger than the size of a galaxy, producing a steady luminosity exceeding that of the Sun by 12 orders of magnitude.

After the discovery of neutrino oscillations by observing natural (solar and atmospheric) neutrino sources, oscillations were also measured with neutrinos produced in nuclear reactors and particle accelerators. Oscillation measurements provide constraints on the neutrino "mixing parameters" (*2*, *3*), that is, on the composition (in terms of $\nu_{1,2,3}$) of neutrinos of different flavors, and on the mass-squared differences, $m_2^2 - m_1^2 = 8 \times 10^{-5}$ $(\mathrm{eV}/c^2)^2$ and $|m_3^2 - m_2^2| = 2 \times 10^{-3}$ $(\mathrm{eV}/c^2)^2$. Here, masses are given in energy units, where $m = E/c^2$; 1 eV is the typical binding energy of molecules and corresponds to roughly one-millionth of the electron mass, $m_e c^2 = 0.5 \times 10^6$ eV. Oscillation experiments cannot determine the absolute values of the masses, and current data do not allow one to discriminate between the two "hierarchies," $m_1 < m_2 < m_3$ and $m_3 < m_1 < m_2$. An upper limit on the mass of the most massive neutrino, $m \leq 2$ eV/c^2, is set by measurements of radioactive decay of tritium (*4*). A similar upper limit is obtained from surveys of the large-scale distribution of galaxies: The universe is filled with a "neutrino background," a relic of the big bang, and if neutrinos were too massive, they would have suppressed the formation of large-scale structures in the universe (*5*).

A model explaining the origin of neutrino masses and mixing does not yet exist (*3*). To construct such a model, large radioactive-decay experiments are planned in order to measure the absolute neutrino mass scale (*4*), and large oscillation experiments involving reactors and specially designed accelerator beams are planned for determining the mass hierarchy (and for accurate determination of the mixing parameters) (*6*). These experiments will also try to ascertain whether the mixing properties of neutrinos and of their antiparticles, antineutrinos, are identical. Answering these questions would be important for the construction of a model accounting for neutrino mass and mixing. It may also be relevant for answering another open question—why our universe appears to be composed mainly of particles and not of antiparticles (*7*).

According to the theory of stellar evolution, stars more massive than the Sun by a factor of 10 or more end their lives with an explosion, a supernova, that ejects most of the star's mass and leaves behind a dense "neutron star" remnant of roughly 1 solar mass. Theory predicts that most of the energy generated by the explosion would be carried away from the star by neutrinos. This prediction was confirmed (*1*) with the detection in 1987 of neutrinos emitted by the supernova SN 1987A, which exploded in the Large

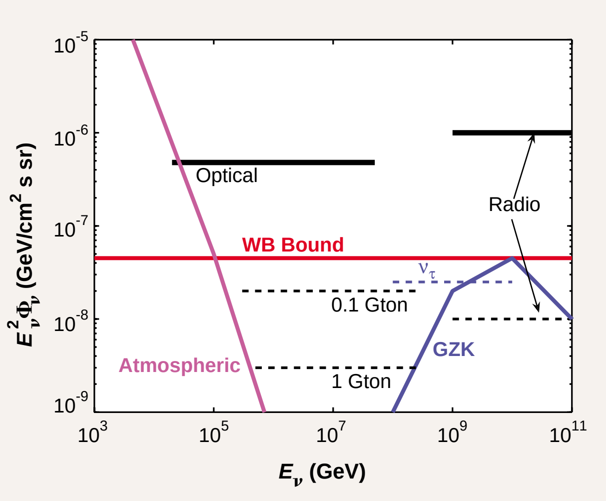

Fig. 2. The cosmic-ray upper bound on the extra-Galactic high-energy neutrino intensity ($\nu_\mu + \nu_\tau$ assuming ν_e:ν_μ:ν_τ = 1:1:1 flux ratios), compared with experimental upper bounds (solid lines) provided by optical detectors under water or ice and by radio detectors, and with the expected sensitivity (dashed lines) of various detectors: 0.1 gigaton and 1 gigaton under water/ice optical detectors, radio detectors, and ground arrays of particle detectors (sensitivity to ν_τ). The intensity Φ_ν is the number of neutrinos of given energy E_ν (measured in GeV = 1000 MeV) crossing in 1 s a unit area (1 cm^2) of a detector observing a solid angle of 1 sr of the sky. A detailed description of the experiments is given in (*8*). The curve marked GZK shows the neutrino intensity expected to be produced by the interaction of high-energy cosmic-ray protons with the cosmic microwave background, the relic radiation of the big bang. Also shown is the atmospheric neutrino intensity, which is produced by cosmic-ray interactions in the atmosphere and constitutes the main background.

Magellanic Cloud, a small satellite galaxy of our own Galaxy, the Milky Way, lying at a distance of some 150 thousand light-years away.

The characteristic energy of neutrinos produced in the Sun or in supernova explosions is on the order of megaelectron volts (1 MeV = 10^6 eV), which is the characteristic energy released in the fusion or fission of atomic nuclei. The detection of MeV neutrinos from sources well outside our local Galactic neighborhood, at distances ranging from several million light-years (the typical distance between galaxies) to several billion light-years (the size of the observable universe), is impossible with present techniques. To extend the distance accessible to neutrino astronomy to the edge of the observable universe, several high-energy neutrino telescopes are currently being constructed deep under ice or water. These telescopes are designed for the detection of neutrinos with energies exceeding terraelectron volts (1 TeV = 10^{12} eV) and are planned to reach effective masses exceeding 1 gigaton (*8*).

The sources targeted by high-energy (≥1 TeV) neutrino detectors are "cosmic accelerators," in which particles are accelerated to extreme energies. The existence of cosmic-rays, high-energy particles that are produced in astrophysical objects and are observed as they hit and interact with Earth's atmosphere, has been mentioned above. The sources of these particles have not yet been identified, and the mechanisms that lead to particle acceleration are not well understood. One of the major goals of ≥1-TeV neutrino detectors is to resolve these open questions.

Particle-acceleration theories are most challenged by the highest-energy particles observed (*9*). These particles are most likely protons, and their energy exceeds 10^{20} eV, or 100 million TeV. Although there are a variety of astrophysical objects suspected of being "cosmic accelerators" (Fig. 1A), only two types of sources are known that may be capable of accelerating protons to 10^{20} eV: gamma-ray bursts (GRBs) and active galactic nuclei (AGN). These objects lie at cosmological distances, billions of light years away and are the brightest known objects in the universe (Fig. 1B). Although GRB and AGN models are generally successful in explaining most observations, they are largely phenomenological, and major questions remain open. These include the mechanisms by which gravitational energy is harnessed to power the sources, and the mechanism of particle acceleration.

A direct association of cosmic-rays with their sources is difficult: Magnetic fields in interstellar and intergalactic space deflect the electrically charged cosmic-rays, which, therefore, do not travel on straight lines and do not point back to their sources. Neutrinos, on the other hand, are electrically neutral and therefore travel on straight lines and do point back to their sources. Whatever the cosmic accelerators are, they are expected to be sources of high-energy neutrinos and therefore to be identifiable by their neutrino emission. This expectation is based on the fact that the interaction of high-energy cosmic-rays with radiation or matter leads to the production of neutrinos. High-energy protons, for example, may interact with photons to produce pions, particles that decay and produce muon and electron neutrinos.

Observations of high-energy cosmic-rays provide a means for estimating the expected high-energy neutrino flux and hence the detector size required to measure it. The observed cosmic-ray flux sets an upper bound to the neutrino flux produced by extra-Galactic sources (*9*), which implies that gigaton neutrino telescopes are needed to detect the expected extra-Galactic flux in the energy range of ~1 to ~1000 TeV, and much larger effective mass is required at higher energy (Fig. 2). A flux comparable to the bound at ~1 to ~1000 TeV would produce hundreds of events per year in a gigaton detector. A few tens of events per year are expected in a gigaton telescope if GRBs are the sources of high-energy protons. These events will be correlated in time and direction with GRB photons, allowing for an essentially background-free experiment.

Detection of high-energy neutrinos with the next generation of telescopes will probe the most powerful cosmic accelerators, including GRBs and AGN, and will allow study of the physical mechanisms powering them. It will also provide new tests of neutrino oscillation theory and probes of fundamental physics that are not available with terrestrial, man-made sources: Flavor measurements of high-energy neutrinos will contribute to the determination of the mixing parameters (e.g., to resolving the mass hierarchy ambiguity and to testing for differences in particle and antiparticle behavior) (*10*). The angular dependence of neutrino detection rate may allow testing for deviations from standard model predictions of the neutrino-nucleon interaction cross section at energies not accessible to terrestrial accelerators (*8*). Detection of neutrinos from GRBs could be used to test the simultaneity of neutrino and photon arrival to an accuracy of ~1 s. This would allow the validity of the underlying assumption of special relativity—that photons and neutrinos have the same limiting speed—to be determined with an accuracy of one part in 10^{17}, and the validity of the weak equivalence principle—the basic assumption of general relativity according to which photons and neutrinos should experience the same time delay as they pass through a gravitational potential—to be measured with an accuracy better than one part in 10^6 (*9*). Previous applications of these ideas to supernova 1987A yielded much weaker upper limits, on the order of 10^{-8} and 10^{-2}, respectively (*1*). Finally, neutrino telescopes may contribute to the detection of "dark matter," unseen particles that were not detected in laboratories on Earth and are believed to contain most of the mass in the universe (*11*), through the detection of neutrinos produced by annihilation of dark-matter particles.

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PERSPECTIVE

Neutrino Astrophysics Experiments Beneath the Sea and Ice

Francis Halzen

Neutrino astronomy beyond the Sun was first imagined in the late 1950s. A neutrino detector at the bottom of Lake Baikal, the deployment of detectors in the Mediterranean Sea, and the construction of a kilometer-scale neutrino telescope at the South Pole exemplify current efforts to realize this dream.

Our universe exhibits nuclear processes far more violent than those that can be created by earthbound particle accelerators. Throughout the cosmos, nature accelerates elementary particles to energies in excess of 10^{20} electron volts, equivalent to a macroscopic energy of 50 joules carried by a single elementary particle. We have no idea where these particles, most likely protons, originate or how they are accelerated to such high energies.

There are several problems when using high-energy particles, or cosmic rays, to carry out astronomy. Because cosmic rays are electrically charged, their paths become scrambled by pervasive galactic and, in some cases, intergalactic magnetic fields, so their arrival directions at Earth do not reveal their exact origin. This is why the cosmic ray puzzle persists almost a century after the discovery of radiation from space. The flux of particles with energies high enough to undergo minimal deflection is so small that sources have proved impossible to observe directly up to now. The Auger detector covering several thousand square kilometers of the high plateau in Argentina may collect such events with sufficient statistics (*1*).

Cosmic rays are also challenging astronomical messengers for another reason: They self-destruct in collisions with universal microwave background photons. As a result, they only reach us from our nearby cosmic neighborhood. Very-high-energy photons share this problem too. For example, greatly improved techniques to collect TeV-energy photons, using the atmosphere as the detector, now probe the universe to redshifts of only $z \sim 0.1$.

However, after the discovery of cosmic neutrinos in the 1950s in the radiation of nuclear reactors, many realized that they did not have the same limitations as charged cosmic particles and photons. Neutrinos had the potential to be ideal cosmic messengers. Unfortunately, building a neutrino telescope has turned out to be a daunting technical challenge (*2*).

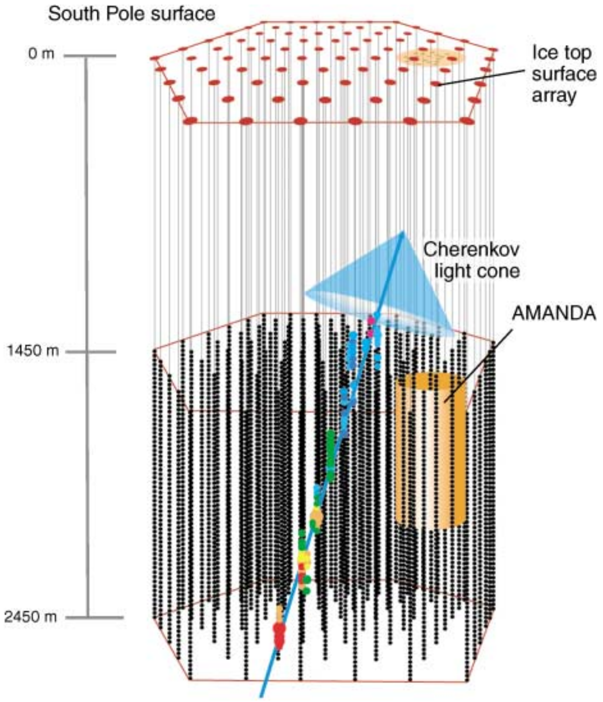

Fig. 1. Design of the IceCube kilometer-scale neutrino observatory. Red dots represent air shower detectors laid out on the surface ice sheet for calibration and shielding of the deep ice detector. IceCube consists of 4800 digital optical sensors (black dots) viewing a cubic kilometer of ice between 1450 and 2450 m. The orange cylinder indicates the volume of ice instrumented by 677 AMANDA sensors. The colored dots show the response of the detector to the Cherenkov light radiated by a simulated 10-TeV muon track. The colored dots (red to purple in rainbow order) indicate the arrival time of the light, red lighting up first; their size is proportional to numbers of photons. The track has been initiated by a neutrino that interacted below the detector after traveling through Earth from a northern source.

With essentially no mass and no electric charge, the neutrino is similar to the photon as a cosmic messenger. It differs in one important attribute, however: Its interactions with matter are extremely feeble. This can be advantageous in that high-energy neutrinos may reach us unscathed from the edge of the universe, from the inner neighborhood of black holes, and, hopefully, from the nuclear furnaces where cosmic rays are born. They may tell us about cosmic sites never "seen" and let us peer into the hearts of black holes.

Unfortunately, this feeble interaction with matter makes cosmic neutrinos also very difficult to detect. Trillions of neutrinos fly through our body every second. On average, one high-energy neutrino produced in cosmic ray interactions with atmospheric nuclei will stop within each of us in a lifetime. Immense particle detectors are required to collect cosmic neutrinos in sufficient numbers to be statistically significant to pursue science. By the 1970s it was clear that a cubic-kilometer neutrino detector would need to be constructed to reveal the neutrinos produced by cosmic rays interacting with background microwave photons. Up-to-date estimates for observing cosmic sources such as quasars or gamma ray bursts, unfortunately, point at the same exigent requirement (*3*).

Given the size of the detector required, efforts concentrated on transforming large volumes of natural water into Cherenkov detectors that catch the flashes of light produced by the rare neutrinos that interact in or near the detector. After an effort that spanned more than two decades, building the Deep Underwater Muon and Neutrino Detector (DUMAND) in the sea off the main island of Hawaii unfortunately failed (*2*). However, it paved the road for later efforts by developing many of the detector technologies in use today, and by inspiring the deployment of a smaller instrument in Lake Baikal (*4*). Its successful operation bodes well for efforts to commission neutrino telescopes today in the Mediterranean: ANTARES (Astronomy with a Neutrino Telescope and Abyss Environmental Research) (*5*) and NESTOR (Neutrino Extended Submarine Telescope with Oceanographic Research) (*6*).

The first telescope on the scale originally envisaged by the DUMAND collaboration has been realized instead by transforming a large volume of the extremely transparent natural deep Antarctic ice into a particle detector, the Antarctic Muon and Neutrino Detector Array (AMANDA). AMANDA, in operation since 2000, represents a proof of concept for the kilometer-scale neutrino observatory, IceCube, now under construction (*7*).

Even extremely high-energy neutrinos will routinely stream through the detectors without leaving a trace; the unlucky one that makes a direct hit on a nucleus in the water or ice will create muons as well as electromagnetic and hadronic

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secondary particle showers familiar from accelerator experiments. The charged remnants will radiate a glow of blue light, dubbed Cherenkov radiation, that will spread through the natural ice over hundreds of meters. The origin of this radiation is the same as that of the blue glow shining from the water shielding nuclear reactors. Neutrino astronomers embed optical sensors into Antarctic ice to detect the faint light from a nuclear reaction initiated by a single neutrino. The light pattern reveals the direction of the neutrino, making neutrino astronomy possible. Among the secondaries, muons are of special interest because the mean free path of the most energetic muons can exceed 10 km. The effective detector volume thus exceeds the instrumented volume for muon neutrinos.

In general, a neutrino telescope must be (i) kilometer-size to detect the low fluxes of neutrinos from cosmic sources, (ii) transparent enough to allow light to travel through a widely spaced array of optical sensors, (iii) deep enough to be shielded from surface light and radiation, and (iv) affordable. Only deep dark oceans and glaciers of ice satisfy these constraints. Pure, highly transparent, and free of radioactivity, Antarctic polar ice has turned out to be an ideal medium to detect neutrinos. The difficulty of the remote site has been overcome by exploiting the infrastructure of the U.S. National Science Foundation's Amundsen-Scott South Pole Station.

AMANDA is the initial stage and proof of concept for a kilometer-scale neutrino observatory, IceCube, now under construction at the South Pole. IceCube will instrument a cubic kilometer of ice surrounding the AMANDA detector (Fig. 1). Its basic detector component is a photomultiplier housed in a glass pressure vessel, somewhat larger than the size of a basketball (Fig. 2B). Photomultipliers transform the Cherenkov light from neutrino interactions into electric signals by the photoelectric effect. The signals are captured by a computer chip that digitizes the shape of the current pulses and sends the information to the computers collecting the data, first by cable to the "counting house" at the surface of the ice sheet and then via magnetic tape or, in the case of more interesting events, by satellite to the IceCube Data Warehouse in Madison, Wisconsin. One can think of IceCube as 4800 freely running computers sending time-stamped digitized images of the light they detect to the surface. The local clocks in the sensors are kept calibrated with nanosecond precision. This information allows the scientists to reconstruct neutrino events and infer their arrival directions and energies. The detector components transform a cubic kilometer of ice at a depth of 1450 to 2450 m into a cosmic neutrino detector (i.e., 1 mile below the surface and ¼ mile above bedrock).

Optical sensors produced at collaborating institutions in the Northern Hemisphere are shipped to the international Antarctic center in Christchurch, New Zealand. These are later transported to the South Pole by way of the port at McMurdo, Antarctica. Drillers use a 5-MW high-pressure jet of hot water to melt a hole in the ice, roughly half a meter wide and 2.5 km deep, in less than 2 days. Because ice is an excellent insulator, the water does not freeze for several days, ample time to deploy the optical sensors attached to cables that will power them and will also transmit their digital signals to the surface (Fig. 2B). Each of 80 holes will hold 60 sensors evenly spread over 1 km between depths of 1450 and 2450 m.

With some 650 optical sensors in place since February 2000, the existing AMANDA detector has been collecting neutrinos at a steady rate of four per day. These "atmospheric neutrinos" are the by-product of collisions of cosmic rays with the nitrogen and oxygen in the northern atmosphere. Note that at the South Pole one observes neutrinos that originate in the Northern Hemisphere, looking through Earth (used as a filter) to select neutrinos from other particles. No photons, or any other particles besides neutrinos, can traverse the whole planet to reach the detector. The signals from the atmospheric neutrinos do not yet yield information about astronomy, but they are calculable and can be used to prove that the detector performs as expected. As in conventional astronomy, AMANDA will have to look beyond the atmosphere for cosmic signals; AMANDA data are now scrutinized for hot spots in the northern sky that may signal cosmic sources.

Starting in the Antarctic summer of 2004–2005, IceCube deployments have been steadily augmenting the AMANDA instrumentation. As of January 2006, IceCube consists of 604 digital optical modules distributed over nine strings and 32 surface cosmic ray detectors. The hardware and software worked "out of the box" and revealed the first atmospheric neutrinos in early February 2006. The collaboration is now analyzing its first 6 months of data. Over the next four seasons, IceCube will transform the ice into the kilometer-scale neutrino observatory that is required for neutrino astronomy. However, detector elements deliver information as soon as they are deployed, and thus IceCube will deliver a kilometer-square year of integrated observations of the Northern Hemisphere by 2008–2009.

After extensive research and development (R&D) efforts by both the ANTARES and NESTOR collaborations in the Mediterranean, there is optimism that the technological challenges to build neutrino telescopes in deep seawater have now been met. Both Mediterranean collaborations have demonstrated their capability to deploy and retrieve optical sensors. The initial deployments targeted R&D of the detector components and in situ study of the water. The deployed optical sensors could also be operated as a particle detector. Both collaborations have reconstructed downgoing cosmic ray muons with the optical modules that were deployed for R&D tests. Although the instrumentation was too limited to detect neutrinos, both collaborations validated their detector designs by detecting cosmic ray muons.

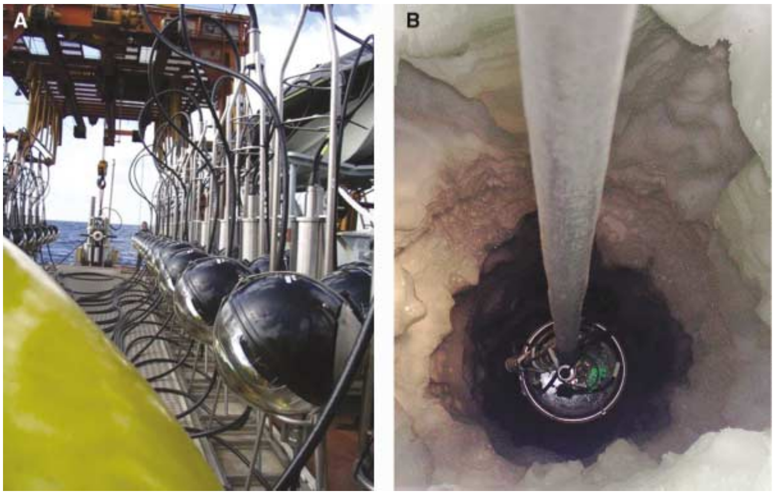

Fig. 2. Deployment of optical sensors (10-inch photomultiplier tubes encased in a centimeter-thick glass pressure housing) by ANTARES in water (**A**) or by IceCube in (temporarily melted) ice (**B**).

The final construction of the ANTARES detector, which will have a similar size as AMANDA, started in February 2006. It is conveniently located at a depth of 2400 m close to the shore near Toulon, France. The detector will consist of 12 strings, each equipped with 75 optical sensors mounted in 25 triplets. The collaboration has by now deployed two strings that were connected by submarine to cables transmitting the data via a junction box to shore. The strings have been successfully and reliably taking data. The completion of the detector is foreseen about 1 year from now. The beginning of operation of ANTARES marks a historic milestone by opening the Southern Hemisphere, and hence the galactic center, for neutrino astronomy. Also, NESTOR is expected to augment its prototype installation in the near future.

Furthermore, a European Union–funded design study dubbed KM3NeT is intended to create a technical design report for the construction of a kilometer-scale detector in the Mediterranean Sea, complementary to IceCube at the South Pole. KM3NeT is a common effort of the Mediterranean projects, including the Neutrino Mediterranean Observatory (NEMO) in Catania, Italy, that has already done R&D toward a kilometer-scale detector. The 3-year study started early this year. The recent project's inclusion in the Road Map of the European Strategy Forum and Research Infrastructures (ESFRI) represents an important step toward the realization of the project. The start of construction of KM3NeT is envisaged for the beginning of the next decade, in time for concurrent operation with IceCube.

As is the case for conventional telescopes, neutrino telescopes inevitably view the universe through Earth's atmosphere. Cosmic rays interacting with atmospheric nuclei produce a uniform background of neutrinos that must be separated from those of cosmic origin. AMANDA, while too small to reveal cosmic sources, has successfully exploited atmospheric neutrinos as a calibration beam. Whereas AMANDA collected some 5000 neutrinos with energy up to 100 TeV, in only a few years IceCube will collect several hundred thousand neutrino atmospheric events with energies of 0.1 to 1000 TeV, well in excess of those observed in particle physics laboratories. Exploiting this guaranteed beam, neutrino "telescopes" will thus also open a new chapter in particle physics. Particle discoveries with natural neutrino beams include neutrino mass. Even in the absence of a discovery, the experiment will be able to test basic principles such as Lorentz symmetry and the equivalence principle with a sensitivity improved by more than two orders of magnitude over present experiments. They may reveal Planck-scale physics (*8*).

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10.1126/science.1136504

PERSPECTIVE

Cosmic Rays: The Highest-Energy Messengers

Angela V. Olinto

The origin of the most energetic particles ever observed, cosmic rays, will begin to be revealed in the next few years. Newly constructed ultrahigh-energy cosmic ray observatories together with high-energy gamma-ray and neutrino observatories are well positioned to unveil this mystery before the centenary of their discovery in 2012. Cosmic ray sources are likely to involve the most energetic phenomena ever witnessed in the universe.

Cosmic rays have a long history, starting in 1912 when Victor Hess lifted electroscopes in balloons to 5-km altitudes and determined that the mysterious ionizing radiation was coming from space and not from Earth. Early cosmic ray physicists used this natural flux of high-energy protons to discover a number of elementary particles, such as the positron, the muon, and the pion, by observing them in cloud chambers and photographic emulsions at high altitudes, where the flux at high energies is less attenuated. By 1938, Pierre Auger showed that very-high-energy cosmic rays trigger extensive air showers in Earth's atmosphere, distributing the original cosmic ray energy among billions of lower-energy particles that arrive together on the ground. In 1962, the Volcano Ranch array led by John Linsley observed a cosmic ray event with an energy of tens of joules or about 10^{20} eV. Four years later, Greisen in the United States (*1*) and Zatsepin and Kuzmin in the USSR (*2*) predicted the abrupt steepening of the cosmic ray spectrum above 10^{20} eV as a result of cosmic ray interactions with the newly discovered cosmic microwave background (CMB). In his landmark article, Greisen announced that the measurement of such a flux steepening would clarify the origin of ultrahigh-energy cosmic rays (UHECRs) by showing its "cosmologically meaningful termination."

A range of different techniques have allowed the observation of cosmic rays from energies just below 10^9 to 10^{20} eV (*3*). Up to 10^{14} eV, direct detection is feasible with balloon and space experiments. Above this energy, the flux is too low for space-based detectors, and cosmic rays are studied by observing their air-shower development. Direct detection shows that at low energies the cosmic ray flux is modulated by the solar cycle through the magnetic heliosphere, which shields the solar system from charged particles below about 10^9 eV. From a few GeV (1 GeV = 10^9 eV) to a few PeV (1 PeV = 10^{15} eV), the cosmic ray spectrum is well described by a power law of spectral index –2.7—i.e., the number of cosmic rays arriving on Earth per unit time, area, solid angle, and kinetic energy, E, is $J(E) \propto E^{-2.7}$. At higher energies, the spectrum steepens to $J(E) \propto E^{-3}$ and the transition region is called the "knee." At about 10^{18} eV the spectrum hardens again, giving rise to a feature named the "ankle." Finally, at about 10^{20} eV, the "cosmologically meaningful termination" predicted by Greisen, Zatsepin, and Kuzmin is expected as these UHECRs lose energy through pion production in interactions with the CMB radiation. This final feature is named the GZK cut-off after its originators. The exact position and shape of each of these features is presently under intense research, because they give clues to the cosmic ray production and propagation mechanisms.

Composition studies at low energies exposed the diffusive history of cosmic ray nuclei as they propagate through the Galaxy. Spallation products of abundant nuclei are much more abundant in cosmic rays than in solar system material; for example, cosmic rays Li, Be, and B—produced mainly by the spallation of C and O—are 5 orders of magnitude more abundant than their solar values. The overabundance, together with spallation cross-sections, shows that cosmic rays have traversed from 5 to 10 g/cm^2 as they propagate in the Galaxy, corresponding to trajectories of ~1 Mpc (equal to 3×10^{24} cm) in length, which is much larger than the thickness of the galactic disk (~ 0.4 pc).

While at energies below 10^{15}eV, cosmic rays are dominated by light nuclei (protons and helium); above the knee, the composition seems to become heavier. This transition to heavier elements is expected in models where cosmic rays propagate diffusively in the galactic magnetic field with a probability of escape that depends on rigidity (i.e., ratio of energy to the charge). Within this picture, the knee would represent the transition from confined trajectories to trajectories that escape the Galaxy and thus produce the change in the spectral index. Tests of this model and alternative proposals are currently under scrutiny by a number of observatories. Leading this effort is the Karlsruhe Shower Core Array Detector (KASCADE) experiment, which uses electromagnetic, muonic, and hadronic particle detectors focused on studying air showers in the energy range around the knee (10^{15} to 10^{17} eV). These data provide evidence for a transition from light nuclei to heavier ones, with a hint of iron becoming dominant just above 10^{17} eV (*4*). A high-energy extension named KASCADE-Grande will reach 10^{18} eV to test this indication in the very near future. Further in the future, low-energy extensions of UHECR observatories such as the Auger Muons and Infill for the Ground Array (AMIGA) and High-Elevation Auger Tele-

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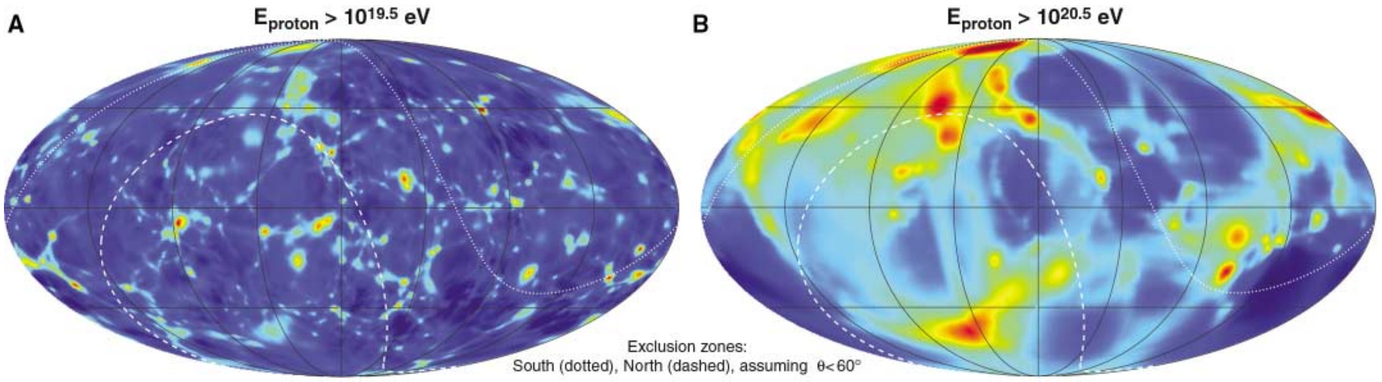

Fig. 1. Sky maps of predicted arrival directions of UHECR with energies of about (**A**) $10^{19.5}$ eV and (**B**) $10^{20.5}$ eV, assuming sources correlate with the dark-matter distribution. The map is a density contrast of arrival events in a log scale ranging from $10^{-2.2}$ (in blue) to 1 in red. [Image courtesy of (*8*)]

scope (HEAT) projects at the Pierre Auger Observatory and the Telescope Array Low-Energy (TALE) extension project of the Telescope Array plan to bridge the study of cosmic rays from just above the knee to the ankle region and beyond.

Among the many proposals for the origin of cosmic rays, the leading candidate for the acceleration of galactic cosmic rays is stochastic shock acceleration in supernova remnants (SNRs), based on a first-order Fermi acceleration mechanism that evolved from a 1949 proposal of Enrico Fermi. SNR shock acceleration naturally generates a power law spectrum of about the right slope, has the necessary energetic requirements, and may explain the observed composition trends (*5*). A clear confirmation of this picture is still lacking, but indirect support for this model has recently accumulated. Chandra satellite x-ray images of SNRs Tycho and SN1006 have indicated that relativistic electrons gain energy in a very thin region at the boundary of SNRs, where magnetic fields reach several hundred microgauss (*6*). More recently, the High-Energy Stereoscopic System (HESS) Imaging Atmospheric Cherenkov Telescope (IACT) array has produced the first images of SNRs in TeV gamma rays. Most notable is the image of RX J1713.7-3946 (*7*), in which it is clear that SNR shells emit TeV gamma rays, consistent with the evidence that they are produced by the decay of neutral pions at the sites of high-energy hadronic interactions. To clearly discriminate between the smoking gun of hadronic acceleration and the production of TeV gamma rays by electronic inverse Compton scattering, it is important to extend the spectrum of RX J1713.7-3946 below the energy threshold of HESS. This should be achieved in the near future by the Gamma-Ray Large-Area Space Telescope (GLAST) satellite, which is scheduled to launch in 2007.

Even if shock acceleration in supernova remnants is responsible for accelerating cosmic rays up to the knee, it is hard to imagine that this mechanism can reach much beyond ~10^{16} eV. At the highest energies, even more powerful sources seem to be required. In addition, as the energy of the primary cosmic ray increases, the effect of the galactic magnetic field on the particle trajectory decreases. As cosmic rays reach energies of ~10^{19} eV and above, trajectories should point back to cosmic ray sources—i.e., cosmic ray astronomy should become possible. Thus far, observations show an isotropic distribution of arrival directions up to the highest energies observed. With no indication of the galactic plane or other nearby structures, this isotropy argues for an extragalactic origin for the highest-energy particles. If UHECRs (above 10^{18} eV) originate in extragalactic sources distributed equally throughout the universe, the distribution of arrival directions in the sky will be isotropic to first order, given that protons of 10^{18} eV can traverse the entire universe unimpeded. As observations of cosmic rays from 10^{19} to 10^{20} eV begin to accumulate in statistics, the effect of the GZK feature should induce a marked change in the distribution of arrival directions of UHECRs. Instead of an isotropic universe, we should see the anisotropic galaxy distribution in our local 10- to 100-Mpc volume.

Fig. 2. A water Cherenkov tank of the Auger Observatory in the Argentinean Pampa Amarilla.

Figure 1 shows the predicted change in anisotropies in the arrival-direction distribution of UHECRs as the observed energy changes from $10^{19.5}$ to $10^{20.5}$ eV. These figures were produced (*8*) assuming that UHECR sources trace the dark-matter distribution in the universe. The contrast at the highest energies is only a factor of 2, which underscores the challenge of charged-particle astronomy: the observation of small anisotropies as the cosmic ray flux reaches below 1 particle per km^2 per century. Newly constructed and future UHECR observatories will answer this challenge by covering areas of 3000 km^2, such as the southern site of the Pierre Auger Observatory, and even larger areas, as proposed for the Northern site and space missions.

UHECRs are detected by means of two main techniques: ground arrays (of scintillators or water Cherenkov tanks) and fluorescence telescopes. Ground arrays sample the extensive air shower as the secondaries reach the ground. The largest arrays to explore UHECRs include Haverah Park (1967 to 1987), Sydney University Giant Air-Shower Recorder (SUGAR) (1968 to 1979), Yakutsk (1991 to present), and the largest before the Pierre Auger Observatory, the Akeno Giant Air-Shower Array (AGASA). The 111 surface detectors of AGASA covered 100 km^2 and operated for just over a decade (1990 to 2004), reaching an exposure of 1.6×10^3 L during the project's lifetime (the unit of exposure, L = 1 km^2 sr year, is named after J. Linsley). An alternative technique based on atmospheric fluorescence was pioneered by the Fly's Eye detector, which in 1991 observed an event with energy 3×10^{20} eV. The fluorescence technique was further developed by the High-Resolution Fly's Eye

(HiRes) experiment, which reached an exposure slightly higher than the AGASA exposure in the recent past. These observatories detect the fluorescence of nitrogen molecules in the atmosphere as the shower develops above the ground. Mirrors focus the fluorescent ultraviolet light onto photomultiplier tubes that record the fast-moving shower pattern in the atmosphere. This technique, unlike ground arrays, can observe the shower maximum directly. However, it has a low duty cycle that works best during clear moonless nights.

Since the prediction of the GZK feature in 1966, progress in the field has been hindered by the experimental challenge of reaching exposures greater than 10^4 L. The HiRes and AGASA observatories gave conflicting results on the existence of the GZK feature (*9–11*), hampered by the low statistics and systematic discrepancies in the energy scale (*12*). The exposure challenge will be faced soon by the completion of the southern site of the Pierre Auger Observatory (*13*). When completed in 2007, the Southern Auger Observatory in the Mendoza province of Argentina will cover 3000 km^2 in a ground array of water Cherenkov detectors (Fig. 2) overlooked by four fluorescence telescope sites. This first hybrid detector uses the strengths of both techniques: the high statistics and geometrical aperture of the ground array with the high-quality reconstruction of 10% of showers observed with the fluorescence telescopes. Auger South has been accumulating data during construction and should reach 10^4 L by 2008. In this exposure range, Auger South will provide high statistics measurement of the spectral features together with composition estimates between $10^{17.5}$ and 10^{20} eV. In addition to resolving the conflict over the shape of the UHECR spectrum around the GZK feature, Auger South will also help determine the transition from galactic to extragalactic cosmic rays expected to occur between 10^{17} and 10^{19} eV. The precise spectral and composition measurement over this wide range of energies will constrain the injection spectrum and composition of proposed UHECR sources as well as the effect of source distribution and magnetic fields on the propagation of UHECRs from source to Earth.

Auger South will explore the 10^4-L exposure range during most of its lifetime and should make a precise measurement of the long-awaited "cosmologically meaningful termination." In addition, neutrino telescopes such as the Antarctic Impulsive Transient Antenna (ANITA), Super Radio Ice Cherenkov Experiment (SuperRICE), IceCube, Low-Frequency Array (LOFAR), and possibly the Square-Kilometer Array (SKA), will explore the predicted neutrino flux from the interactions of UHECRs with the CMB that give rise to the GZK feature. The multimessenger approach to the origin of UHECRs will establish their origin as extragalactic and begin to focus on possible sources. A key ingredient in the unveiling of UHECR sources will be the detection of anisotropies in the arrival distribution of UHECRs (Figs. 1 and 2); a new generation of observatories is now being planned to achieve this goal. On the ground, the proposed Northern site of the Auger Observatory would cover an area of 4000 square miles (10,370 km^2) to reach 10^5 L in the next decade. In space, fluorescence telescopes are being planned to look down on Earth from the International Space Station or from free-flying dedicated satellites. The era of 10^5 L will open the new field of charged-particle astronomy.

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14. I acknowledge funding by the NSF through grants NSF PHY-0457069 and by the Kavli Institute for Cosmological Physics under NSF PHY-0114422 at the University of Chicago.

10.1126/science.1136640

PERSPECTIVE

The Very-High-Energy Gamma-Ray Sky

Felix Aharonian[1,2]

Over the past few years, very-high-energy gamma-ray astronomy has emerged as a truly observational discipline, with many detected sources representing different galactic and extragalactic source populations—supernova remnants, pulsar wind nebulae, giant molecular clouds, star formation regions, compact binary systems, and active galactic nuclei. It is expected that observations with the next generation of stereoscopic arrays of imaging atmospheric Cherenkov telescopes over a very broad energy range from 10^{10} to 10^{15} electron volts will dramatically increase the number of very-high-energy gamma-ray sources, thus having a huge impact on the development of astrophysics, cosmology, and particle astrophysics.

It has been said that very-high-energy (VHE) gamma-rays—photons with energy in excess of 100 billion eV (*1*)—represent the "last window" onto cosmic electromagnetic radiation. They are copiously produced, thanks to various electromagnetic and hadronic interactions, in nature's machines, cosmic TeVatrons and PeVatrons, which are capable of accelerating electrons, protons, and nuclei to TeV and PeV energies. Unlike charged particles, gamma-rays freely propagate through the intergalactic radiation and magnetic fields across most of the universe. Finally, they are detectable by space-borne or ground-based detectors. These three features make very-high-energy gamma-rays unique carriers of astrophysical and cosmological information about the most energetic and violent processes in the universe.

Gamma-ray astronomy addresses a diverse range of topics in modern astrophysics and particle astrophysics, including (i) acceleration and radiation processes in extreme conditions, in particular in relativistic outflows like jets and winds formed in the vicinity of black holes and pulsars; (ii) the origin of galactic and extragalactic cosmic rays; (iii) the nature of nonthermal transient phenomena such as gamma-ray bursts; (iv) cosmology, by probing the cumulative extragalactic background light that contains information about the history of formation of galaxies and the first stars; and (v) fundamental physics, including the indirect search for dark matter and signals from primordial black holes.

Earth's atmosphere is not transparent to gamma-rays; therefore, an ideal detector would be located in space. However, space platforms offer limited detection areas, effectively constraining the study of weak cosmic gamma-ray fluxes to energies below 100 GeV. At higher energies, an alternative method of detection of cosmic gamma-rays becomes available, based on the registration of secondary showers produced by interactions of primary gamma-rays with Earth's atmosphere, seen either directly or through their Cherenkov radiation. Because the speed of ultrarelativistic electrons exceeds the speed of light in the atmosphere, these electrons produce an ~1° cone of blue Cherenkov light that forms a pool on the ground with a radius of about 120 m. The Cherenkov signal of air showers is very faint and brief; the flash lasts only a few nanoseconds. Consequently, Cherenkov telescopes must have large (>>1 m^2)

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optical reflectors to image the Cherenkov light onto a very fast multipixel camera sensitive to the blue light with a typical pixel size of 0.1° to 0.2° and a field of view of several degrees. The total number of photons collected in the resulting image is a measure of energy, the orientation of the image correlates with the arrival direction of the gamma-ray, and the shape of the image contains information about the origin of the primary particle (a proton or gamma-ray). These three features, coupled with the huge (as large as $0.1\ \text{km}^2$) detection area, comprise the basis of the Imaging Atmospheric Cherenkov Telescope (IACT) technique.

The first reliable VHE gamma-ray signal from an astronomical object, the Crab Nebula, was detected using the IACT technique in the late 1980s by the Whipple 10-m-diameter telescope located on Mt. Hopkins, Arizona (*2*). Over the next 15 years, major efforts to detect gamma-rays were made by the Cherenkov Array at Themis (CAT), Collaboration of Australia and Nippon (Japan) for a Gamma-Ray Observatory in the Outback (CANGAROO), High-Energy Gamma-Ray Astronomy (HEGRA), Whipple, and some other groups. However, they only managed to detect 10 or so VHE gamma-ray sources, some tentatively. So, despite several notable results, in particular the discovery of gamma-rays from blazars (*3*), these efforts did not present a huge breakthough. More sensitive detectors were needed badly.

In the mid 1990s, the concept of stereoscopic arrays, consisting of two or more 10-m-diameter class telescopes observing the flashes simultaneously from different directions, was recognized as the most promising approach that can facilitate dramatic improvement in the sensitivity and push the detection threshold down to 100 GeV (*4*). Although the power of the stereoscopic approach was convincingly demonstrated by the HEGRA system of small aperture telescopes, it was the High-Energy Stereoscopic System (HESS) that elevated the status of the field to a level of a truly observational (astronomical) discipline. HESS, an array of four 13-m-diameter IACTs equipped with an ~5° field of view imagers, was completed in 2004 (Fig. 1). It covers a broad energy band from 100 GeV to 100 TeV with an angular resolution of a few arc minutes and minimum detectable energy flux approaching 10^{-13} erg $\text{cm}^{-2}\ \text{s}^{-1}$. Whereas HESS observes sources mainly from the Southern Hemisphere of the sky, Major Atmospheric Gamma-Ray Imaging (MAGIC)—a single very large Cherenkov telescope—targets the Northern Hemisphere (Fig. 1). Soon the Very Energetic Radiation Imaging Telescope Array System (VERITAS), a new stereoscopic array consisting of four IACTs, will start taking data from Southern Arizona.

Presently, several galactic and extragalactic source classes are established as TeV gamma-ray emitters (see Fig. 1). One of the remarkable achievements of HESS was the discovery of shell-type structures of young supernova remnants (see Fig. 2), in particular of the object RXJ1713.7-3946 (*5*, *6*), which was earlier reported as a TeV gamma-ray source by the CANGAROO collaboration (*7*). This result supports the early theoretical predictions that galactic cosmic rays must have deep links to supernova remnants, namely, that they are accelerated by shocks in the shells of material lost during the supernova explosion.

HESS has also revealed that many young pulsars are surrounded by extended regions of VHE gamma-ray emission. Some show an energy-dependent morphology (*8*), such that the source size reduces as the photon energy increases (see Fig. 2). This can be explained by the energy losses of electrons and strongly supports the paradigm that electrons are accelerated to 100 TeV energies and beyond at the site of the termination of the cold ultrarelativistic pulsar wind.

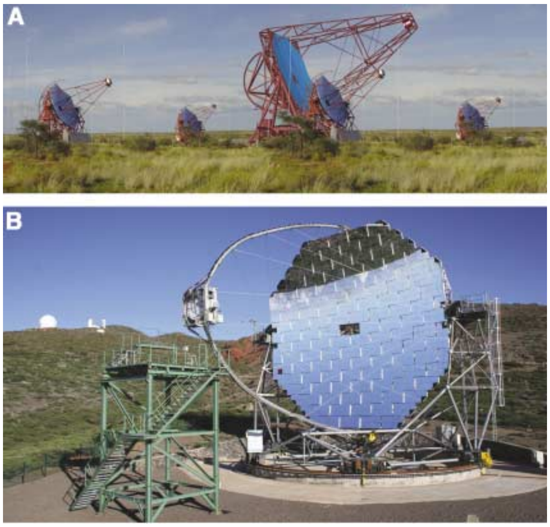

Fig. 1. HESS and MAGIC. **(A)** HESS is a stereoscopic array of four 13-m-diameter Cherenkov telescopes located in Namibia. The central telescope is an artistic view of the new 28-m-diameter dish, presently under construction. [Image, W. Hofmann] **(B)** MAGIC is a single 17-m Cherenkov telescope located on the Canary Island of La Palma. In 2007, it will be accompanied by a second similar telescope. This will allow observations of gamma-rays sources in a stereoscopic mode. [Image, P. Sawallisch]

If a particle accelerator is located in a binary system with a luminous optical star, the interactions of accelerated electrons with the optical starlight or with the dense stellar wind proceed on time scales of hours or even less. Thus, such binary systems allow continuous watch of the complex acceleration and magnetohydrodynamic processes such as the creation and termination of relativistic outflows related to the compact object. This may be a "cold" pulsar wind in the case of a neutron star or a "hot" jet in the case of a black hole. So far, three compact binary systems have been detected by the HESS (*9*–*11*) and MAGIC telescopes (*12*). The so-called Microquasar LS 5039, a binary star system where one component is a black hole, shows a strictly periodic component, which implies that the source behaves as a "TeV clock" with a period of 3.908 ± 0.002 days, which perfectly coincides with the known orbital period of the system (*11*).

Although gamma-rays from discrete objects reveal the locations of cosmic accelerators, one should expect also a diffuse component of radiation caused by interactions of relativistic particles, which escape their production sites, with the surrounding dense gas regions like giant molecular clouds (GMCs). The HESS observations indeed revealed TeV gamma-ray emission which correlates with several distinct GMCs in the central 200 parsec region of our Galaxy (*13*). The gamma-ray map of this region indicates an inhomogeneous spatial distribution of the runaway protons, which can be explained by the high activity of the particle acceleration in the past, related, for example, to the compact radio source Sgr A* or to a recent supernova explosion in the galactic center. Sgra A*—presumably a supermassive black hole (SMBH) located in the dynamical center of our Galaxy—can be responsible also for the compact TeV gamma-ray source detected by the Whipple, CANGAROO, HESS and MAGIC groups, although some other explanations, including the hypothetical Dark Matter Halo of the Galaxy, cannot be excluded.

More compelling evidence for production of gamma-rays in SMBHs recently was obtained from Giant Radiogalaxy M87. The detected variability of TeV gamma-ray emission on time scales of days implies that we "see" gamma-rays arriving from regions located in the vicinity of a 3×10^9 solar mass black hole (*14*).

SMBHs, the powerhouses of active galactic nuclei (AGN), play a key role in production of VHE gamma-rays observed from AGN. The gamma-ray horizon of the universe, the most distant observable region, is determined by gamma-ray interactions with the diffuse extragalactic background light (EBL); at very high energies, it is limited to distances of only several hundred megaparsecs. That is why the first extragalactic TeV gamma-ray sources were dominated by relatively nearby blazars—AGN with jets directed toward Earth. Although the effect of relativistic Doppler boosting provides orders of magnitude enhancement of the gamma-ray flux, the nearby location of these sources is crucial to minimize absorption of gamma-rays and thus make feasible their detection. With reduction of the energy threshold of detectors down to <100 GeV, one should expect a substantial increase in

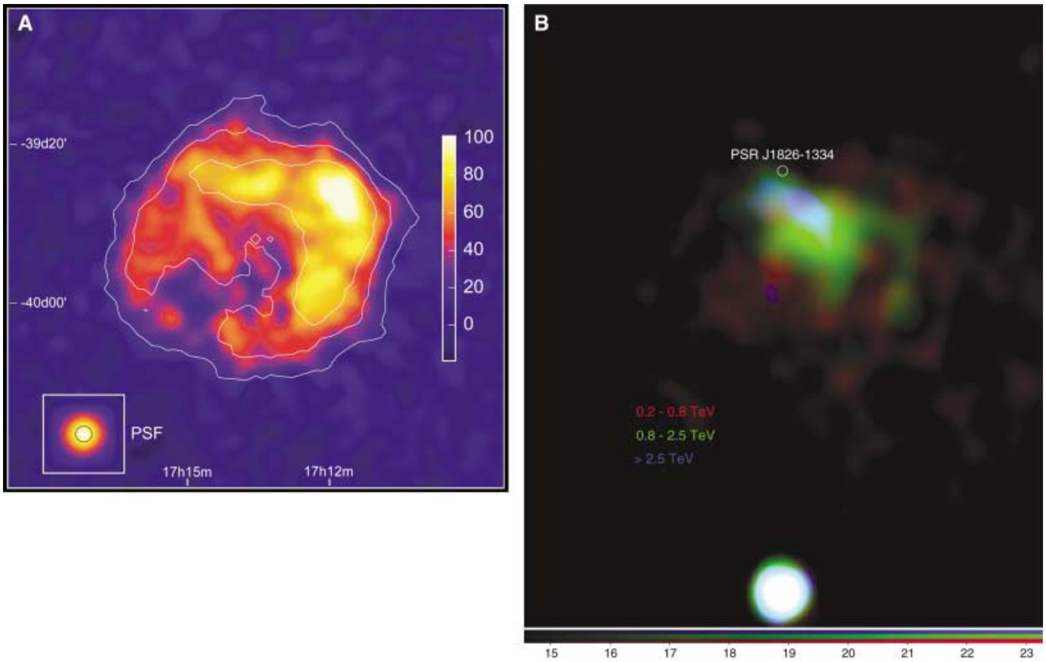

Fig. 2. (**A**) The gamma-ray image of the young SNR RX 1713.7-3946 obtained with the HESS telescope array. The shell-type morphology is clearly seen (*5*). [Image, D. Berge] (**B**) The gamma-ray images of the extended gamma-ray source HESS J1825-137 shown for different energy bands: below 1 TeV (red), between 1 and 2.5 TeV (green), above 2.5 TeV (blue). The source most likely associates with the pulsar PSR J1826-1334, the location of which is indicated by the white point. Gamma-ray production proceeds mainly through the inverse Compton scattering of these electrons on photons of the 2.7 K cosmic microwave background radiation. Because the latter fills every corner of the cosmos, the spatial and energy distributions of electrons can be derived from VHE gamma-ray data unambiguously and with very high precision—a unique case in astrophysics when the nonthermal particle distributions are obtained without any additional assumptions. The bright point-source to the south is the microquasar LS5039. [Image, S. Funk]

the numbers of extragalactic objects detected. Intensive searches conducted by HESS and MAGIC collaborations over the past 2 years have doubled the number of known TeV blazars. Some are quite distant, reaching redshifts of z = 0.20. This result was used to derive a robust upper limit on the EBL flux at optical/near-infrared wavelengths so as to constrain cosmological models concerning the formation and evolution of galaxies and the first stars (*15*).

Planning of the next generation of IACT arrays (*16*) has two objectives: (i) an order-of-magnitude improvement of the flux sensitivity in the standard (0.1 to 10 TeV) energy regime and (ii) an aggressive expansion of the energy domain of IACT arrays in both directions, down to 10 GeV and up to 1 PeV.

If one limits the energy to ~100 GeV, the performance of the telescope arrays can be predicted with confidence. Namely, a sensitivity well below 10^{-13} erg cm^{-2} s^{-1} and angular resolution of 1 to 2 arc min can be achieved by a stereoscopic array consisting of a very large number (up to 100) of 10-m-diameter class IACTs. One may predict, based on the extrapolation of the HESS results, that such an instrument will discover and resolve hundreds, or perhaps even thousands, of galactic TeV sources. On the other hand, such an array would gain a lot if the energy threshold can be reduced to 30 GeV. This would considerably increase the number of scientific objectives, in particular increase the distance range of detectable extragalactic objects up to redshifts of z = 1, as well as considerably improve the flux sensitivity around 100 GeV. This can be achieved by somewhat larger 15-m-diameter class telescopes, installed at quite high altitudes of 3 to 4 km above sea level. The construction of such a powerful detector could be completed on relatively short time scales because it would be based on current technologies.

Further reduction of the energy threshold down to 10 GeV or even less is possible but requires a different approach: operation of 30-m-diameter class telescopes in a robotic regime at extremely high altitudes of 5 km above sea level—for example, on the Atacama Large Millimeter Array (ALMA) site (*17*) and design of high quantum efficiency focal plane imagers. The energy range from several GeV to 30 GeV has very specific astrophysical and cosmological objectives: exploration of highly variable nonthermal phenomena, in particular in the remote universe at redshifts of z = 5, as well as in compact galactic objects like microquasars. The successful realization of such a gamma-ray timing explorer, hopefully during the lifetime of the Gamma-Ray Large-Area Space Telescope (GLAST) mission (*18*), would be a great achievement for gamma-ray astronomy.

Finally, it is important to develop a ground-based technique allowing simultaneous coverage of a substantial fraction (1 steradian or more) of the sky. The most realistic approach uses very large water Cherenkov detectors installed at altitudes of ~4 km (*19*). The feasibility of this technique has been convincingly demonstrated by the Milagro collaboration. The prospect of exciting discoveries of yet unknown VHE transient phenomena in the universe fully justifies the efforts toward the construction of a large field-of-view ground-based gamma-ray detector(s). These instruments will be complementary to GLAST and the future large-volume (km^3-scale) high-energy neutrino detectors.

References and Notes

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