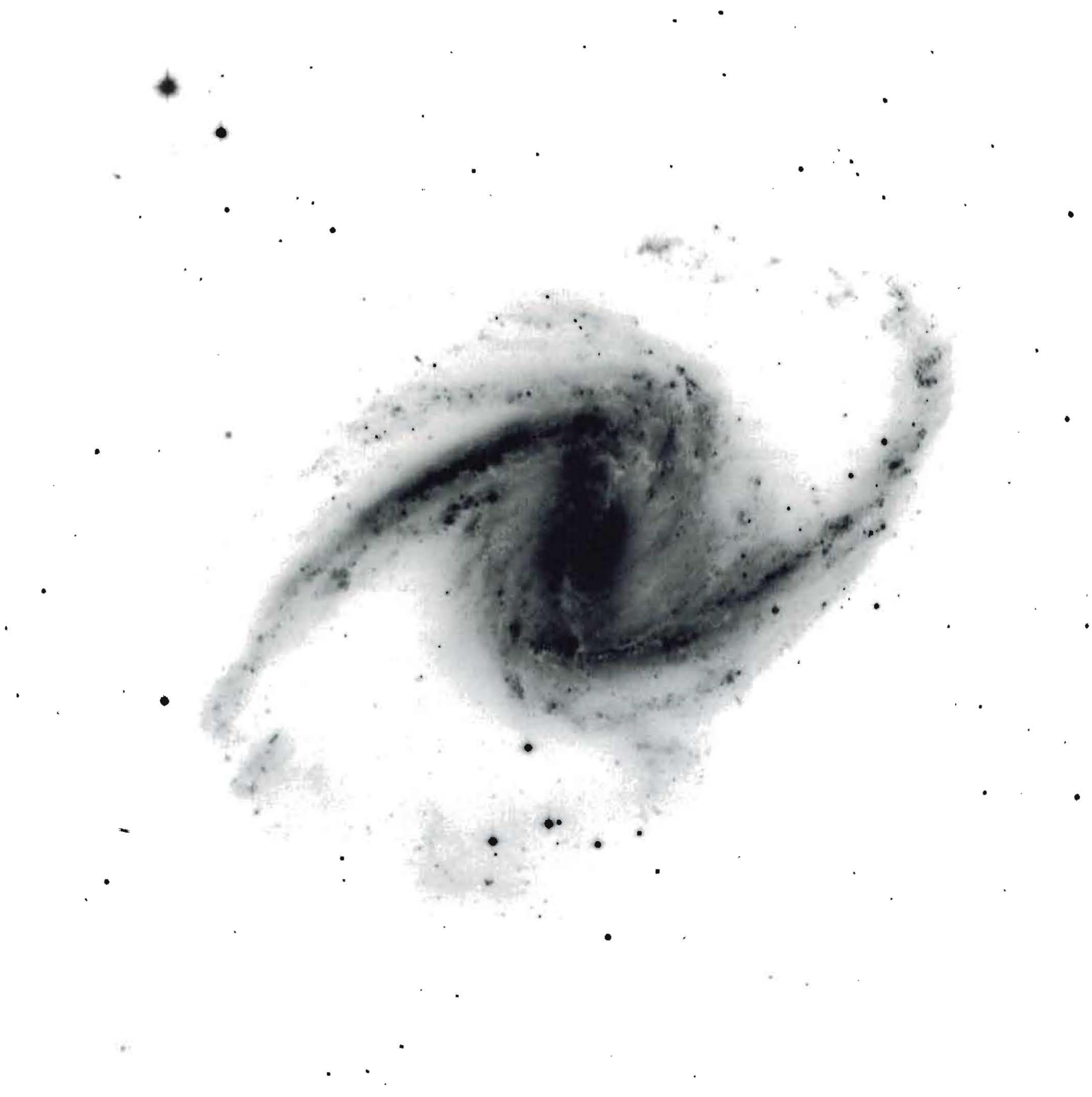
To Catch a Ghost

The Search for Particles of Dark Matter

by Marcia Bartusiak



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Angela Da Silva received little advance warning. The young engineering physicist had only twenty-four hours to arrange a cross-country flight from San Francisco to Oak Ridge, Tennessee, a town noted for its nuclear research facilities, legacy of the city's wartime founding. Time was of the essence. Da Silva had to pick up three particle detectors, recently fabricated by the scientific-instrumentation manufacturer ORTEC, and get them back to the Center for Particle Astrophysics, her employer in Berkeley, California, as quickly as possible. She seemed an unusual courier. With her straight, shoulder-length hair, light-brown in color, and big horn-rimmed glasses, Da Silva resembled a cerebral Alice in a scientific wonderland. And she was enmeshed in a curious adventure.

The detectors themselves, wholly composed of the purest germanium, looked like shiny oversized doorknobs. Each was cylindrical in shape, about two inches in diameter and three inches long. ORTEC personnel had spent weeks on their construction, first purifying the newly mined germanium and then slowly growing the jumbo metallic crystals from a heated melt.

Within a day of her arrival at Oak Ridge, Da Silva had the three detectors safely nestled in the trunk of her rental car, ready for a drive across the country. Flying the detectors back to California on a plane was out of the question. The Earth is continually bombarded by high-speed cosmic rays racing in from space, energetic atomic particles that can slice right through an atomic nucleus and change one atom into another. That's bad news for germanium detectors. Whenever a cosmic ray occasionally slams into an atom of germanium, it can create tritium, a radioactive form of hydrogen that interferes with the germanium's performance as a particle detector. In fact, to help cut down on this contamination in Oak Ridge while awaiting Da Silva's pickup, ORTEC temporarily stored each of its finished detectors in a local tourist attraction, a deep underground cavern far removed from cosmic-ray impacts.

With the detectors, Da Silva traveled back to California speedily. The first night of driving took her to Memphis. The next day she relentlessly pushed westward through Arkansas and Texas. Over the following two days, at a steady sixty-mile-per-hour pace, she proceeded through Arizona and into California. She didn't take the most direct route, through the Sierra Nevada mountain range, because the flux of cosmic rays sharply increases at high elevations. In order to minimize the germanium's exposure to cosmic rays while it was tucked away in the trunk of her car, Da Silva chose a more southerly itinerary. This kept her at the lowest altitude possible, ensuring that the thickest, most protective atmosphere stood between the detectors and the incoming rays. Such are the tasks of modern-day astronomers—a far cry from their past concerns with lenses and mirrors. The germanium detectors were eventually placed hundreds of feet below the Earth, within a cavernous chamber set beneath California's Oroville Dam, a massive earthen structure located about 125 miles northeast of Berkeley. Together these crystals served as the heart of an underground telescope. The detectors passively stood watch, awaiting the arrival of an exotic particle that could slice right through the Earth, as if this planet were an insubstantial mist, and signal the presence of a heretofore unknown material spread throughout the universe.

Combining her skills as a journalist with an advanced degree in physics, Marcia Bartusiak has been covering the fields of astronomy and physics for more than a decade. A contributing editor for *Discover* magazine, she is also the author of *Thursday's Universe*, a layperson's guide to the frontiers of astro physics and cosmology. In her compelling new book *Through A Universe Darkly*, Bartusiak explores how we learned what the universe is composed of, from the composition of stars to the evidence for dark matter. In this excerpt, Bartusiak outlines how researchers search for evidence of dark matter particles when they aren't even sure what they are.

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Dark Matter

Astronomers suspect that there is something more out in space, an unknown substance that has come to be called dark matter. But so far this elusive substance can be detected only by observing and measuring its gravitational effects on visible matter: galaxies within a cluster move around unusually fast, and yet stay together as a cluster; stars situated at the outer edges of spiral galaxies orbit faster than theory would predict and yet do not fly off. Reservoirs of unseen matter, with their added gravitational clout, must exist to keep these galaxies and stars in check. Since everything from protons to planets exerts gravity, the dark matter can, in theory, be made of pretty much anything. Many astronomers are perfectly happy with the idea that it consists of more or less ordinary stuff — hosts of faint brown dwarfs, perhaps, or dark, Jupiterlike planetoids. On the other hand, a number of physicists are convinced that this unseen material is of the particle (rather than the planetary or stellar) variety. "For one thing, our theories of how the visible stars formed have a hard time making all those brown dwarfs and 'Jupiters,'" says particle-physicist-turned-cosmologist David Seckel. "Also, from what we know about galaxy formation, it is hard to create a universe filled with galaxies if dark matter is solely composed of ordinary matter." But until a new elementary particle, with all the requisite properties, is actually cornered, all thoughts of a new type of matter, invisible and relentlessly aloof as it drifts through the cosmos, must be regarded as conjecture. [See box on page 11 for a list of possible particle candidates.]

All skepticism would disappear, of course, if Earthbound scientists could catch one of the hypothetical particles in a terrestrial laboratory. For many years, no one thought this would be possible. But major advances in both detector technology and low-temperature physics at last allow researchers to pursue their dream of snaring the elusive matter directly, and at relatively moderate expense. At a time when particle physics experiments have come to involve hundreds of physicists and technicians, at costs of hundreds of millions of dollars, dark-matter experiments can be conducted within a small laboratory setting. More than a dozen groups around the globe either have started looking or are gearing up for the search. They can be found in Great Britain, France, Switzerland, Germany, Italy, Canada, Japan and the United States. All are panning for celestial gold.

Underground Astronomy

A drive from Berkeley, California to the Oroville Dam on the Feather River takes about two hours. Visitors first travel northeast along Interstate 80 to Sacramento, the state capital, then take Route 70 northward through the numerous nut and fruit orchards that stretch along California's lush Central Valley. The dam itself, spanning one and a half miles across its top, was at one time the largest earthen dam in the world. It was built in the late 1950s to curb the devastating floods that often tore through this rich agricultural region.

Situated at the very base of the dam, with six hundred feet of earth overhead, is a manmade cavern, bored out of the rock to house the dam's imposing power station. The cavern can be reached by either driving or walking down a long concrete-walled tunnel, eerie in its dim fluorescent lighting. Water slowly drips down the walls, forming the occasional stalactite. Throughout the tunnel can be heard the echoing hum of the massive turbines, incessantly spinning ahead. "It's almost like a Jules Verne novel, as if we're about to tap into the energy of the Earth," exclaims Alan Smith.

With his casual striped shirt, suede shoes, and long greying hair pulled back in a hippielike ponytail, Smith maintains a relaxed and comfortable air. A physicist with the Lawrence Berkeley Laboratory since 1953, Smith is a specialist in low-level radiation detection. He first became interested in such studies for medical research, analyzing the long-term effects of low-level radiation exposure on the human body. Later, as the Apollo astronauts brought back their many rock samples from the Moon, the lab came to specialize in creating pristine environments for keeping such specimens well protected from stray radioactive contaminants.

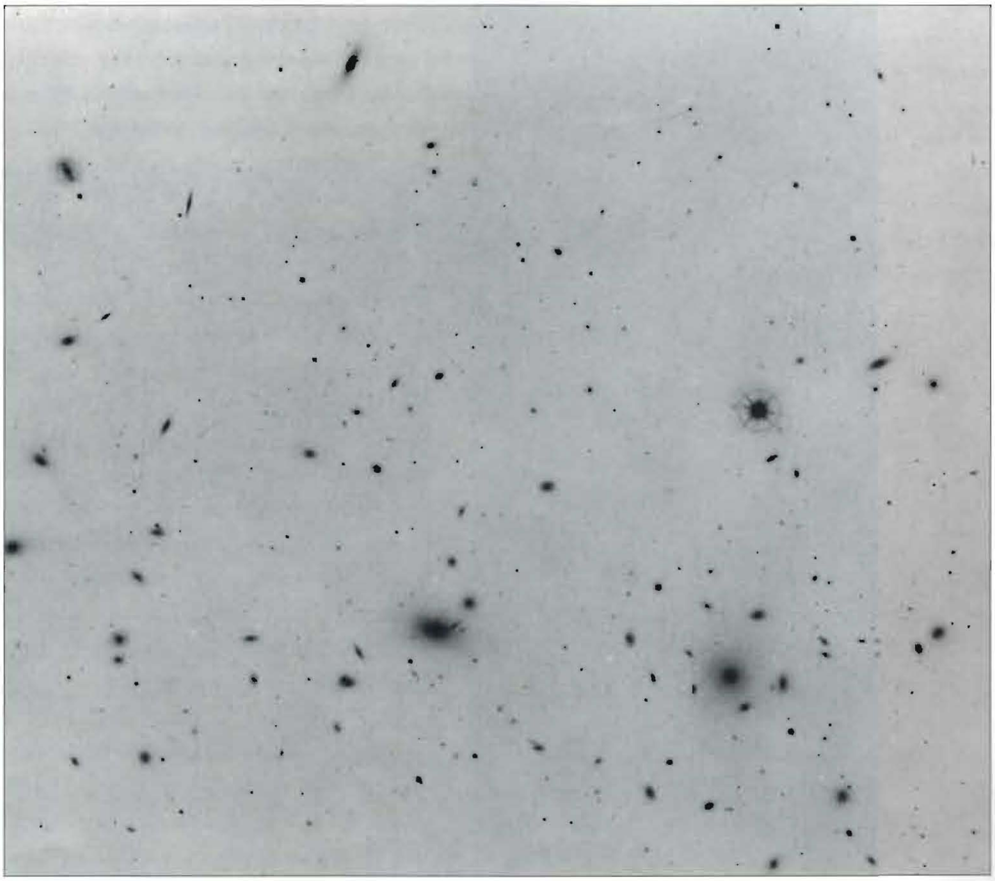
Smith is keen to answer questions, and in a melodic voice he recalls myriad facts with ease. "More than one hundred years ago, Lord Kelvin, the word of God at that time, or close to it, declared that the Earth was roughly one hundred million years old. He arrived at that number by determining how long it must have taken for the Earth to have cooled to its present state. But that number conflicted with the age of some well-known rocks. Are we at a similar impasse?" asks Smith as he briskly walks down the tunnel to the very bowels of the Oroville Dam. "We almost had it all figured out — the contents of the universe. Now, we're discovering that we don't know 90 percent or more of what's out there. It's crazy."

At the end of the tunnel is a vast hall, as big as a football field. Amidst the six giant turbines, huge orange cranes ploddingly move back and forth overhead. "Here's our little universe," declares Smith with pride, pointing to an elevated platform at one end of the cavernous chamber, a former visitor's gallery transformed into a physics laboratory. The operation resembles a small construction site. Dominating the scene is a neat, cubelike pile of lead bricks, each side spanning some three and a half feet. A special detector resides inside the lead pile and is cooled by a continual wash of liquid nitrogen that is fed in from large vats set nearby. As if providing life support, dozens of wires and cables stream out of the pile and connect into banks of amplifiers and other assorted instruments that are arranged like rows of books on metal shelves.

No one event will ring any bells in this experiment — only data gathered over weeks, months, even years. Researchers here are looking for a unique signal that rises above all the extraneous instrumental noise, a signal that broadcasts the presence of a new, exotic particle that is filling the universe and posing as the dark matter.

Smith first came to Oroville, a booming gold-mining camp in the nineteenth century, in connection with other work. After a sizeable earthquake shook the area in 1975, he went to the dam to measure the levels of radon in selected wells on the site. A popular theory had suggested that sudden changes of radon levels near an earthquake's epicenter might serve as a quake predictor. Years later the site came to mind when researchers from the Lawrence Berkeley Laboratory and the University of California, Santa Barbara were looking for a special spot to observe a rare phenomenon, known as double beta decay, deep underground far from interfering radiation such as cosmic rays.

If this rare event did take place, the physicists didn't expect to see more than a few events over an entire year. Thus it was crucial to get all spurious background noises at Oroville as quiet as possible. It was as if they were trying to distinguish the sound of a single drop of water amidst the roar of a pounding surf. The Oroville researchers applied a number of strategies to sharpen their "ears." With the Oroville chamber lodged beneath several hundred feet of rock



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and earth, disruptive cosmic-ray counts automatically drop a thousandfold. The entire instrument is also surrounded by a bevy of scintillators, which, if struck by a particularly resourceful cosmic ray flying in from above, briefly lights up, with the flash recorded by a photomultiplier tube. Such outside noise can then be ignored. Some particles are stopped in their tracks even beforehand, by the piles of lead stacked up around the detector. To do this effectively, the Oroville team used lead from a unique mine in Missouri with high concentrations of primordial lead, which is little contaminated with the radioactive uranium or thorium that can introduce false detector signals. A similar experiment, run for a while in the Homestake mine in South Dakota, went so far as to have its detectors shielded with 450-year-old lead from a sunken Spanish galleon. The Homestake investigators reasoned that any residual radioactivity in the lead induced by cosmic rays would have disappeared after centuries in deep water and that radioactive fallout from nuclear blasts could not have penetrated that far down into the sea.

The most problematic radioactive interference emanated from the experimental components themselves. A germanium crystal can be made extremely pure, limiting impurities in its atomic makeup to less than one part in a trillion, but by the time the germanium ore is mined, grown into crystals, and transported by plane to its user, it is also subjected to a year of cosmic-ray bombardment, which produces such meddlesome contaminants as radioactive tritium.

The double beta decay experiment at the Oroville Dam ran for years, from 1984 to 1988, but the anomalous process was never seen. The effort, though, still had its rewards. During the course of the long measurement, the Berkeley and Santa Barbara scientists came to perceive that their experimental setup could be subtly modified, making it possible to search for some of the dark-matter particles then being hypothesized, particularly the weakly interacting massive particles, or WIMPs.

A dark matter particle is expected to whiz through a detector at nearly two hundred miles per second. With each tick of the clock, millions of these tiny motes, by some estimates, could be flying through each square centimeter of space. It is assumed that, as this intense shower of WIMPs rains down upon the detector crystal (at Oroville, both germanium and silicon have been used), one of the particles will occasionally hit a nucleus in the crystal lattice. And like a set of springs, the lattice should start vibrating under the impact, since the WIMP is expected to have a mass in the same range as an atomic nucleus. A small fraction of the energy from that impact would then be transferred to the electrons in the crystal, making them start flowing as a current. Each crystal that is mounted within the lead pile is monitored by putting an electric field on it and measuring this flow of charge, a method of detection known as ionization detection. Since nearly all the WIMPs will simply pass through the array of crystals as if they weren't there, the pickings will be slim. A single two-pound crystal might experience anywhere from one to one thousand WIMP interactions each day, depending on the nature of the WIMP.

As with the double beta decay experiment, outside interferences can be stopped by taking such precautions as going deep underground and shielding. So delicate is the dark-matter measurement that the researchers' biggest worry is the radioactivity induced in the materials as they are transported to the Oroville site. Learning from its experiences during the double beta decay experiment, the Oroville team arranged for the special mining, processing, and transport of their detector crystals. Upon excavation from a deep mine, the germanium ore, for example, is directly and speedily taken to the processing plant. And as soon as the germanium crystals are fashioned, they are promptly transported to California by car along a low-altitude route, like that of Angela Da Silva. This prevents the crystals from getting any more radioactive than they have to be.

Carrying out the Oroville experiment is fairly automatic. Data is recorded right on site, and the condition of the equipment is monitored hourly. A status report is routinely sent over the telephone lines twice a day — four in the morning, and four in the afternoon — to a computer in Building 29 at the Lawrence Berkeley Laboratory. Once a week, a lab worker drives out to Oroville to retrieve the data tapes and replenish the liquid nitrogen. In its continual perusal of the data, the Oroville team is looking for a distinctive signal that rises above the noisy background and fits the profile of a dark-matter particle.

After several years of nearly continual data gathering, the Oroville Dam experiment has so far ruled out the existence of a special, heavy neutrino that had been theorized, one that required a fourth "family" of particle types. This massive neutrino had been quite popular as a dark-matter candidate in the 1980s, for it was the easiest candidate, theoretically, to consider within the known laws of physics.

A Supercool Solution

Ongoing detection schemes, such as those conducted in the subterranean grotto at the Oroville Dam, have certainly eliminated a number of candidates for the dark matter, but all those possibilities have been mere long shots at best. A perusal of the scientific literature shows that the most sought after dark-matter particles are the WIMPs. Physicists call these particles "well motivated," because they were first invented by particle theorists for reasons totally unrelated to cosmology. And yet astronomers find them quite handy: WIMPs not only explain the dark matter very nicely, they can also generate enough gravity to maintain the universe in an exquisite balance, keeping the cosmos from expanding forever or eventually collapsing — a balance that many cosmologists are attracted to for both scientific and aesthetic reasons. But given current technologies, it is still a dream to think of catching these WIMPs; the sensitivity of the dark-matter detectors must first be improved up to a thousand times to register these ephemeral creatures.

The ionization detectors used at Oroville are just the first step in what physicists in this field envision as a developing line of ultrasensitive dark-matter detectors. The next generation

A Guide to the Dark-Matter Particle Candidates

WIMPs: These particles pop up in equations when theorists try to unify nature's various forces. In such schemes, every particle already known to exist comes to have a partner. The Z particle, for example, has its Zino; the W particle, its Wino; and the photon, its photino. The lightest and most stable of these predicted particles would serve as the dark matter. Each would be roughly as heavy as ten or more protons, yet still be terribly indifferent to ordinary matter, flying right through it. Hence, the name WIMP, for weakly interacting massive particle.

Axion: A particle hypothesized by physicists to handle certain problems arising in the modeling of the strong force, the force that keeps atomic nuclei from flying apart. In a fit of whimsy, theorist Frank Wilczek named it after a laundry additive. A single axion might be more than a trillion times lighter than an electron, but a trillion axions could be stuffed into every cubic inch of space around us, adding up to some substantial matter.

Neutrino: A neutral, phantomlike particle that is emitted during certain radioactive decay processes. Of all the dark-matter particle candidates, only the neutrino is already known to exist. The Big Bang spewed out hordes of them. But, for the moment, no one yet knows whether neutrinos are anything more than mere spots of energy, as Wolfgang Pauli first conceived them in 1930. Neutrinos must have some mass to serve as the dark matter. Several neutrino "observatories," a variety of underground detectors situated around the globe, are now in operation attempting to answer that question.

exact microwave frequency depends on knowing a precise mass for the axion, and current theoretical values are not constrained tightly enough. What the researchers do know is that the axion couldn't weigh much more than a billionth the mass of an electron; otherwise, the neutrino signal that emanated from the spectacular Magellanic supernova of 1987 would have been smothered. ("Heavy" axions would have cooled the supernova so much that the burst of neutrinos emanating from the explosion could not have been seen by underground detectors on Earth.) The axion hunters at Brookhaven scanned the frequencies of one to six gigahertz, using copper cylinders of different sizes and repositioning a sapphire rod in each to subtly adjust the frequency. "It's as if we were looking for a specific station on a radio that has five million channels," says Bruce Moskowitz, a Brookhaven physicist who had collaborated on the project.

Sikivie and his colleagues are continuing the search at the University of Florida. There they operate a microwave cavity ten times more sensitive than the Brookhaven model, tuning it with two ceramic rods. It is a frustrating business, because not seeing a signal does not necessarily mean the axion doesn't exist — only that it is terribly hard to trap. Sikivie estimates that the sensitivity of their axion detector probably has to be improved a few hundredfold before axions can be sighted with assurance. He hopes to accomplish that in the future with the construction of a three-thousand-liter cavity surrounded by a gargantuan magnet formerly used for fusion research at the U.S. Livermore National Laboratory.

Dark-matter detection in the laboratory is tricky in more than just technical ways — funding is scarce, and researchers may spend years developing an instrument that could become obsolete with a change in theory. Very speculative candidates abound, such as "quark nuggets," "shadow matter," and "boson stars." One perpetual contender is the monopole, a particle conceived as a solitary magnetic pole, either a north or a south, but not both. Theoretical wizard Paul Dirac first predicted the monopole's existence more than half a century ago when he contemplated nature's many symmetries. If the universe provides us with separate units of electric charge — the positively charged proton and the negatively charged electron, for example — then it's likely, Dirac surmised, that it also cooked up separate particles of magnetic charge. Monopoles naturally arise in grand unified theories as well. Much like neutrinos, monopoles are now out of fashion as a dark-matter possibility, but detecting just one could change that. A large collaboration of Italian and American scientists is taking a look with the new Monopole, Astrophysics, and Cosmic-Ray Observatory (MACRO), a series of detectors set in a football-sized arena of iron and concrete, located deep inside Italy's Gran Sasso, highest of the Apennine mountain range, sixty miles east of Rome.

Having a variety of instruments is vital to this enterprise, because different materials and techniques favor different types of dark-matter candidates; the greater the assortment, the better the chances that the true dark-matter particle (if that is what the dark matter is truly composed of) will be detected. The trickiest part for dark-matter hunters will be convincing themselves that they have observed a bona fide dark-matter particle with their detector. How can they be absolutely sure the registered event wasn't an instrumental "burp" or a stray cosmic ray? One way would be to look for a small but marked difference in the dark-matter signal over the course of the year. If they are real, dark-matter particles should be hovering around and through our Milky Way galaxy like

Errors and Clues — From Through A Universe Darkly by Marcia Bartusiak.

Telescopes and detectors continue their scans of the heavens. More often than not, the additional bits of evidence these instruments gather daily simply confirm and extend currently accepted models of the universe. But at times a finding can generate new challenges, becoming a piece in the cosmic puzzle that never quite fits in. Such crises in astronomy periodically wax and wane over the decades. In the 1930s Edwin Hubble, after measuring how fast the universe was ballooning outward, turned the clock backwards and calculated how long this expansion could have been transpiring. He was forced to conclude that, based on the evidence, the universe was younger than the Earth! This paradox swiftly disappeared once the art of cosmic distance measurements was refined and advanced, correcting Hubble's initial and mistaken finding. "It's foolish to bet when things are just above the threshold," says theorist Joseph Silk of the University of California at Berkeley. "So many errors creep in." But which of the measurements made today are in error and which are the invaluable clues hinting at a new vision that might lead to a reinterpretation of our cosmic heritage? The process of science does not always provide neat and tidy answers.

of detectors will be cooled to extremely low temperatures — so low, in fact, that whenever a WIMP races through and happens to interact with the detector crystal, the advanced cryogenic instrumentation will be able to discern the resulting heat or vibrations in the wake of the disturbance. A pure-crystalline detector, made of possibly germanium, boron, or silicon, would attempt to spot the heat a WIMP generates when it bangs into an atomic nucleus. After such a collision, a set of phonons, or sound waves, would ripple through the crystal and just slightly raise its temperature. With most of the energy of a WIMP collision going into heating the detector, rather than into ionization, this is a much more efficient means of spotting a WIMP.

The difficulty is in developing a sensor sensitive enough to measure the rise in temperature, which could be as small as a millionth of a degree. This should best be accomplished by cooling the instrument to within a few tens of thousandths of a degree above absolute zero, the temperature at which all molecular and atomic motions presumably cease. The different materials (e.g., germanium, boron, and silicon) would be used to target different dark-matter candidates. Germanium-73, for instance, possesses a nuclear property known as spin, which enables the germanium nucleus to interact more effectively with certain WIMPs, such as photinos. That phonons can be recognized and measured has been confirmed by Berkeley researcher Thomas Shutt, who constructed and ran a cryogenic detector consisting of a small sixty-gram disk of germanium, one and a half inches in width. A pilot run of the supercooled detector system is taking place at Stanford University in a shallow underground facility built especially for this next stage in the dark-matter hunt.

A number of investigators in France, Japan, Germany, Switzerland, Canada, and the United States have taken a completely different approach. They are considering designing boxes containing billions of microscopic grains of superconducting metal, each no bigger than a bacterium, suspended in a nonconducting material. They expect to sight a WIMP when it hits one of the grains; the resulting heat would flip the metal granule from a superconducting state to a normal state. The enormous challenge in this task will be manufacturing an array of grains that are scrupulously uniform and developing the electronics that can distinguish the change of state in just one grain.

Tuning in the Axion

The very first particle candidate for the dark matter, the neutrino, was quite attractive for a number of reasons. For one, unlike all the other particle candidates, the neutrino is already known to exist — the Big Bang spewed out hordes of them. And their unobtrusive nature fit the profile of a dark-matter contender perfectly: They could pass through people and planets as though they were ghosts. But no one is yet sure that neutrinos have mass. And computer simulations show that a universe dominated by neutrinos would probably not have condensed into galaxies the way the real universe did, a discovery that took neutrinos out of the running. These particles will likely remain on the sidelines unless a signal from a neutrino observatory forces physicists to accept the existence of a massive neutrino.

But neutrinos were just the first in a long line of suspects. The axion, a popular candidate, is still waiting in the wings. Trying to corner an axion, though, is fraught with difficulty. For a while, it was thought that axions might be impossible to snare, a notion that was not unreasonable. An axion, if it exists, could whiz through a series of steel bank vaults lined up from here to Pluto and not bump into one atom. How could one possibly catch such a will-o'-the-wisp?

In 1983 an imaginative Belgian named Pierre Sikivie, a theorist with the University of Florida at Gainesville, arrived at a clever solution for catching axions. While teaching a course on electromagnetism, it occurred to him that if an axion passed through a particularly intense magnetic field (roughly 200,000 times that of the Earth's magnetic field), it should decay and emit microwaves at a specific frequency. Inspired by Sikivie's insight, a team of physicists working at the Brookhaven National Laboratory in the United States built an axion detector consisting of a pure copper cylinder surrounded by a superconducting magnet. The cylinder was just the right size — sixteen inches tall and eight inches wide — for resonating at microwave frequencies, much the way an organ pipe resonates at a given frequency when filled with air. According to Sikivie's theory, if an axion passes through such a cylinder, the magnet should make the axion decay. The resulting burst of microwaves would produce hardly more than a trillionth of a trillionth of a watt of power, but that would still be enough to make the cylinder resonate at detectable levels.

After three years of searching, the Brookhaven researchers did not register any axion-related peeps resonating within their cylinder, but they weren't surprised. Tuning into the