Nailing Down Gravity: New ideas about the most mysterious power in the universe
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http://www.discover.com/issues/oct-03/cover/

DISCOVER Vol. 24 No. 10 | October 2003

Long after the human race has vanished or evolved into something else, long after the sun has swollen into a red giant and incinerated Earth 5 billion years from now, at least one human artifact will continue drifting to the far reaches of the galaxy, safely preserved for eternity by the near-perfect vacuum of interstellar space. Pioneer 10, launched in 1972 on what was expected to be a 21-month voyage to Jupiter, is now some 8 billion miles from home. On January 23, tracking stations picked up the last feeble transmission from the probe's plutonium-powered radio transmitter, which can no longer muster a signal strong enough to reach Earth. As project scientists listened to that final fading whisper, they were left to ponder a mystery: The spacecraft seems to be defying the laws of gravity. Pioneer 10 has been slowing down, as if the gravitational pull on it from the sun is growing progressively stronger the farther away it gets.

Question 1: What would happen if you drilled a hole that ran from the North Pole to the South Pole and then dropped a bowling ball into the hole?

Pioneer 10 is not the only spacecraft acting strangely. Pioneer 11, launched in 1973, also slowed down as it pulled away from the sun, right until NASA lost contact with it in 1995. And there's some evidence of similar bizarre effects on two other probes: Ulysses, which has been orbiting the sun for 13 years, and Galileo, which plunged into Jupiter's atmosphere last month. Is it possible that a single, identical malfunction struck all these vehicles? Or is some unknown force in the universe slowing them down? For Michael Martin Nieto, a theoretical physicist at Los Alamos National Laboratory in New Mexico, the mystery involves much more than a few hunks of spacefaring hardware; it reveals that there might be something wrong with our understanding of gravity, the most pervasive force in the universe.

"We don't know anything," he says. "Everything about gravity is mysterious."

Nieto's words are strong for a phenomenon that seems so familiar. After all, the laws set down by Isaac Newton more than 300 years ago describe with unfailing precision everything from the fall of the pages as you leaf through this magazine to the stately gyres of galaxies. Or do they? The usual rules work fine on Earth—tides rise and fall—and fine in our solar system—planets circle the sun. But when astronomers try to use Newton's equations on larger scales, say, to predict the movements of the stars orbiting the center of a galaxy, they get the wrong answers. In every single galaxy ever studied, the stars and gas move faster than Newton's laws say they should, as if gravity from a hidden mass in or around the galaxy were yanking them along, boosting their speed. To make the calculations agree with what is observed, astronomers have been forced into an embarrassing situation. They have to assume that immense amounts of invisible matter surround all galaxies. Astronomers simply call this mystery stuff dark matter. They have no clear idea what it is, but their belief that it must be there is remarkable testimony to their faith in Isaac Newton.

"It's a fudge factor," says Nieto. "And there's a fudge factor in every galaxy."

While the overwhelming majority of astronomers believe in the existence of dark matter, a handful of heretics have begun to question the wisdom of believing in something that no one has ever seen. They want to eliminate the fudge factor, even if that means mounting a full frontal assault on Newton's laws. It's a lonely, unpopular stand, but these heretics may be able to explain why Pioneer 10 is not where we thought it should be.

Question 2: If you fired one bullet straight up (90 degrees from the horizon) and one bullet at a 45 degree angle to the horizon, which would hit the ground first?

Five researchers and I are falling down a narrow mine shaft in utter darkness at 800 feet a minute, pulled by the most mysterious force in the universe. We're in a rattling, battered old metal cage with no lights, tethered to an inch-and-a-half-thick steel cable spooling off a 12-foot-wide drum hundreds of feet above us. Without that cable and other safety mechanisms, we'd hit the bottom of the 2,341-foot-deep shaft at about 120 miles per hour, in predictable and fatal compliance with Newton's laws. They may be imperfect, but there seems to be no escaping those laws, and that is precisely what makes gravity the most singular—and most exasperating—of all nature's forces.

Unlike an electric field, which can be obstructed by any material that has an opposite charge, gravity can't be blocked. Its invisible threads link you to every atom, planet, star, and galaxy in the cosmos. At this very moment the most distant galaxies are tugging at you, and you are tugging them. That is true for every planet and moon, for boulders and trees, even for that ant crawling past you. Nothing can be isolated from gravity's effects, which is why physicists cannot measure the strength of the gravitational force very accurately—only to about five decimal places. That might seem precise, but to physicists, who can track the vibrations of a single atom to nine decimal places, it's slipshod.

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As we descend into the mine, I recall a story that Riley Newman, a physicist at the University of California at Irvine, recently told me. Several years ago, Newman was trying to measure the gravitational interaction between a steel tube and a copper rod hanging from a thin fiber strand inside a vacuum chamber. Because anything with mass exerts a small gravitational force on its surroundings, the steel tube caused the suspended rod to twist the fiber slightly. By measuring the amount of twist, Newman intended to calculate precisely the strength of the force of gravity. But his data came out screwy. The results were way off. Some unknown source of gravity was interfering with the experiment.

"The chart recorder would show a trace that was fairly level and then would climb over the course of an hour or so and level off again," Newman says. "It occurred in the middle of the night, and it wasn't correlated with the steel tube that was our source mass, so it was pretty clear that it wasn't a legitimate signal. But we were extremely perplexed. We tried to think of what could be happening in the middle of the night that could account for it. My students found out what time the campus radio station went off the air, in case that had something to do with it. We checked with the heating-plant people. We checked with the janitorial staff to make sure no one was coming into the lab at that time.

"Then one time at about 3 a.m. one of my students was leaving the laboratory, and as he walked out the sprinklers for the lawn went on, about 10 yards away from our building. He made an estimate of how much mass"—and thus how much gravitational force—"those sprinklers were depositing in the lawn, and it turned out to be just about the right magnitude to account for what we were seeing."

Newman's difficulties pale beside the challenges facing researchers at the bottom of this mine shaft. The cage we're riding in once carried miners to veins of ore so rich in iron that raw chunks of rock could be welded together with an acetylene torch. Now it ferries physicists and other visitors to a $16 million apparatus they've built in a cavern blasted out of greenstone nearly a half mile beneath the hardscrabble town of Soudan, in northern Minnesota. The apparatus is designed to detect dark matter. If the search succeeds, Newton's laws will be vindicated. If not, well, more on that shortly.

With no success yet in directly observing dark matter in the realm that astronomers normally study—the sky—some researchers have instead devised a subterranean trap. They think they can snare some of the stuff because Earth should constantly be passing though clouds of cold dark matter particles, called WIMPs—weakly interacting massive particles. In any given second as many as 100,000 invisible WIMPs should be piercing your thumbnail.

Even 10 years ago most physicists thought it would be impossible to build instruments sensitive enough to detect such particles on Earth. But today the electronics needed for a dark-matter hunt are at least a thousand times more sensitive. And that is why a team of physicists has set up shop in this iron mine. They call their experiment Cold Dark Matter Search II. (CDMS I, a smaller version of the experiment, was built 150 feet underground on the campus of Stanford University.)

On this March morning, not far from the Canadian border, there's no shortage of some cold dark matter—my feet could easily qualify. Long Duong, a newly minted Ph.D. from the University of Minnesota, and I are getting ready to enter the clean room that houses the detectors for more elusive dark matter. We each don full-length disposable bodysuits, two pairs of gloves, two pairs of paper booties, and hairnets. Duong tells me to leave my coffee outside, giving me a momentary flash of an alternate future in which a bumbling journalist ruins a multimillion-dollar experiment when a Styrofoam cup slips from his hand.

The detectors, hockey-puck-size samples of germanium-and-silicon crystal housed in two-foot-long hexagonal instruments, are mostly hidden from view inside what Duong and the other physicists call the icebox. A cooling unit circulates liquid helium around the seven-foot-high, nine-foot-wide cylindrical icebox, chilling the detectors to just 50 thousandths of a degree above -459 degrees Fahrenheit: absolute zero. That makes this one of the coldest places in the universe. Not a spot where you'd want to spill some hot joe. Theorists believe that WIMPs move sluggishly compared with particles like neutrinos or cosmic rays—at about a thousandth the speed of light. If WIMPs exist, and if one hits a silicon-germanium wafer stacked inside one of the hexagonal instruments, the impact should make the crystal lattice in the wafer vibrate ever so slightly, causing a small temperature spike. Any ambient heat would also vibrate the crystal, washing out potential signals. Thus the need for ultralow temperatures.

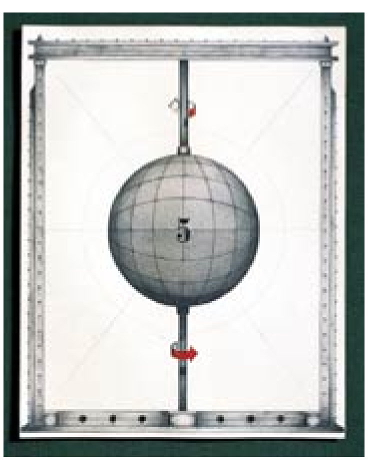
The other major requirement—massive shielding—is fulfilled by the depth of the mine, with its natural barrier of tons of rock between the experiment and the surface 2,341 feet above. The rock blocks cosmic rays—high-energy particles from space that could mimic a WIMP's arrival. (See the September 2003 issue of Discover or Discover.com for more on cosmic rays.) WIMPs, if they exist, would easily penetrate the rock and zip straight through the planet. But physicists hope that a few will hit their detector. Eleven tons of lead and two tons of polyethylene shield the detectors, which weigh just a few pounds, from any radioactivity in the surrounding rock that could create a false signal. The lead was hauled up from a 200-year-old shipwreck, where it served as ballast. Its long burial beneath seafloor sediments isolated it from cosmic rays that could have triggered WIMP-masking radioactivity within the lead. Duong expects the detector will be running in earnest sometime this fall. By the end of next year, at least 10 other dark-matter detectors around the world will also be online. And what if no dark matter is detected? At least a few physicists won't be surprised.

Stacy McGaugh once toed the party line on dark matter and gravity. He was a believer. Then he met Israeli physicist Moti Milgrom. In 1994, while McGaugh was a postdoctoral fellow at Cambridge University in England, trying without success to use dark-matter models to explain the motions of small, dim galaxies, he stumbled into a seminar that changed everything.

"Milgrom happened to come through and give a talk on the subject of modified gravity. I almost didn't go to the talk. I thought, 'Modified gravity? I don't want to hear about this crap.' But I went. And Milgrom, not knowing who I was or what I did, as part of his talk just said, 'Oh, for low-surface-brightness galaxies'—this is what I worked on—'they should do this and this and this.' And that was exactly what I was seeing! So I sort of scraped my jaw off the floor and went back into my office."

Question 3: If you could spin Earth five times faster than its present once-a-day rotation, would gravity increase significantly?

Milgrom, a 57-year-old physicist at the Weizmann Institute of Science in Rehovot, Israel, argues that a fudge factor like dark matter isn't necessary if physicists make just one small tweak to Newton's laws of gravity. He became disenchanted with dark matter in the early 1980s, when he began to wonder if it might be possible to explain the motions of galaxies without filling most of the universe with vast quantities of an undetectable mystery substance. "It's very embarrassing," says Milgrom of the situation astronomers find themselves in today. "I hear even people who adhere to dark matter call this the preposterous universe."



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Milgrom asked a reasonable question: What if the laws of gravity as we understand them don't apply on a galactic scale? After all, the only direct experience we have with Newton's laws has been within the parochial confines of our solar system. Maybe the rules are different for galaxies, where the typical span of a single rotation brackets the time from the dawn of the dinosaurs to the moment you're reading this page.

"We infer that dark matter exists only because we think we understand gravity on these scales," says McGaugh. "If we have the perfect theory of gravity, then the data oblige us to believe that there is unseen matter. On the other hand, we don't have any tests of our theory on those scales except these kinds of data. So you could equally well interpret that to say that the data are telling us that there is something wrong with our understanding of gravity."

Following a few false starts, Milgrom hit on an approach that seemed to reproduce the peculiar movements of galaxies without the need to invoke dark matter. The key was acceleration. Gravity accelerates things. When you jump off a cliff, Earth's gravity pulls you down at a speed that increases every second at a rate of 32 feet per second. Likewise, our sun—and every other star in the sky—accelerates toward the center of the Milky Way galaxy at a rate that works out to about the width of an atom per second every second. That's weak—just 100-billionth as strong as the gravity we feel on Earth. Milgrom proposed that Newton's laws might change at these paltry accelerations. Below a transition acceleration equal to one 10-billionth of a meter per second every second—Milgrom calls it a0—the force of gravity might no longer be directly proportional to acceleration, as decreed by Newton. Instead, gravity might be slightly stronger, proportional to the square of acceleration. With this minor change, which kicks in when accelerations dip below one 10-billionth of a meter per second every second, Milgrom found that he could perfectly predict the motions of galaxies without introducing the fudge factor of dark matter. Stars in galaxies move faster than expected, not because of gravity from invisible matter but from the extra oomph they get as described by Milgrom's law.

Milgrom calls his brainchild MOND, for Modified Newtonian Dynamics. He, McGaugh, and others have used MOND to explain the mechanics of dozens of galaxies. "Dark-matter theorists haven't even made the first step in explaining the host of regularities that MOND explains," says Milgrom. "This is just something they hope they'll be able to do in the future, but they haven't even started. To me it looks hopeless."

Most astronomers refuse to embrace MOND. Milgrom understands: "I think the science community should give any such idea a hard time. If you really want to shake the principles, it shouldn't be an easy matter."

Milgrom also acknowledges that MOND has a serious flaw: It has no connection to any deeper theory. MOND works, but no one has explained why. Newton's description of gravity was part of an enormous theoretical edifice. So was Einstein's. MOND may turn out to be a piece of something larger, but for now it stands alone. "MOND is, I like to think, in an early stage of its development," says Milgrom. "The concept is there. The basic idea is there. Now I'm trying to understand where MOND comes from, because I see it as a derived concept. I think there should be some more basic underlying theory, some idea from which it will follow."

Maybe physicists shouldn't be too surprised if Milgrom turns out to be onto something. After all, Newton's laws have been modified in the past, most famously by Albert Einstein. According to Newton, gravity is a force that acts invisibly and instantaneously between any objects with mass. Einstein had a different thought: There is no gravitational force. What we perceive as gravity is just a geometric effect, a consequence of the way massive objects distort the shape of space-time. That might seem abstract and impossible to visualize—after all, we can't see four dimensions. But look at the graceful parabola traced by water squirting from a sprinkler, or watch a football arcing through the air. Both are following the curves of space-time created by Earth's mass. If Milgrom is right, Newton's and Einstein's laws will be in for some major tweaking. Milgrom suspects that a large part of that tweaking will have something to do with the value of his transition acceleration, a0.

"It turns out that this value has a cosmological significance," says Milgrom. "It is the acceleration you get by dividing the speed of light by the lifetime of the universe. If you start from zero velocity, with this acceleration you will reach the speed of light roughly in the lifetime of the universe. This is a cornerstone of all my searches for an underlying theory. It must be telling us something about the origin of the theory."

There's another mystery MOND might be able to explain—the mystery of Pioneer 10 and 11.

John Anderson, an astronomer at NASA's Jet Propulsion Laboratory in Pasadena, California, was analyzing data from Pioneer 10 and 11 in 1980 when he noticed that both spacecraft were decelerating in a way that violated Newton's laws, as if the sun's gravity had increased in strength. "Something was exerting a force on the spacecraft that we didn't understand," says Anderson. "We thought we'd be able to explain it terms of forces generated by the spacecraft. And I really thought eventually it would go away as we got farther and farther from the sun. But it did not go away."

Anderson continued to monitor the signals, but it wasn't until late last year that he and five colleagues, including Michael Martin Nieto of Los Alamos, published an exhaustive 50-page analysis of the Pioneer mystery. They looked for evidence of onboard gas leaks, software errors—anything that might explain the anomaly. They found nothing. "We tried, and our friends tried, and our enemies tried. And nobody could come up with a smoking gun," says Nieto. "And we've really looked hard."

Question 4: If you dropped a bowling ball from 10 feet up and simultaneously fired a bullet parallel to the horizon, which would hit the ground first?

The Pioneer effect is real. For decades, something has been decelerating the spacecraft—or accelerating it toward the sun—at a rate that is eerily consistent with what MOND would predict: The acceleration is about one 10-billionth the acceleration we feel from gravity on Earth.

"I've been interested in Milgrom's stuff for a long time simply because it's a simple idea, a clever idea," says Nieto. "And I don't care if it's totally wrong; it's been totally useful. MOND has forced people to look much more closely at galaxy composition, dark matter, and gravity than they would have otherwise."

Nieto and Anderson would dearly love to see the launch of a mission dedicated to rigorously testing the Pioneer anomaly. Nieto is already drawing up plans for one and looking for backers. Over lunch at a café in Los Alamos, he talks excitedly about the mission and whether its discoveries might rock the foundations of physics. At one point he flings his arms out to describe the solar sails the spacecraft might have and accidentally whacks a waitress. I ask if he has come up with a name for the project.

"Hey, if she'll fund it, I'll call it the Anna Kournikova," he says. "Seriously, if God came down and said, 'OK now, bet your soul and tell me what's causing the Pioneer effect,' I'd say a systematic error. I would be surprised if we measured something that shows us gravity is acting differently, but I'd be very happy if it was. A physicist has to keep very clear in his mind what he knows, what he thinks he knows, what he's suspicious of, and what he wants. I want Pioneer to be different. Who wouldn't? Of course, I'd love it to be something new. I'd love it. I'd definitely go out and stick my tongue out at my enemies. But that's different than saying I believe it is."

Answer 1: The bowling ball would drop with increasing speed until it reached Earth's center. At that point it would begin to slow until it reached the other side, where it would stop and begin falling again.

Answer 2: The bullet fired at an angle would hit the ground before the one fired straight up.

Answer 3: No. Gravity is related to mass, not rotation.

Answer 4: They would hit the ground at the same time.

For more information about the underground laboratory in Soudan, Minnesota, check out www.numi.fnal.gov/public/brochure.pdf.

Take a virtual tour of the Soudan underground lab: www.hep.umn.edu/~border/soudan2/vtour_js.html.

Visit the Cryogenic Dark Matter Search Web site: cdms.berkeley.edu.

NASA's Pioneer page: spaceprojects.arc.nasa.gov/Space_Projects/pioneer/PNhome.html.

For background on modified Newtonian dynamics (MOND), see www.astro.umd.edu/~ssm/mond and www.aeiveos.com/~bradbury/Astronomy/MOND.html.