Setting Einstein an exam question. *Physicist Francis Everitt has spent most of his career on one experiment to prove Einstein right or wrong.*

Putting Einstein to the Test—in Space

Gravity Probe B—an audacious experiment conceived 30 years ago to test general relativity—nears the launching pad

IN THE FALL OF 1959, THREE SCIENTISTS were sitting on the edge of the men's pool on the Stanford University campus when they came up with a way to test one of the most influential—but least tested—conceptions in 20th-century science: Einstein's general theory of relativity. One of the three, the internationally known physicist Leonard Schiff, was just finishing his usual lunchtime swim when he was introduced by physicist William Fairbank to a new, young faculty member, Robert Cannon. Recalls Cannon: "Leonard pulled himself up on the side of the pool and started talking about this concept he had about testing Einstein's theory on gravity."

Although Schiff presented his notion as little more than a "thought experiment," he knew there was one place where it could be put into practice: space. It was only 2 years after the launch of Sputnik—and the birth of the space era—but the trio already had started planning how to use near zero-gravity space as a lab for its experiment. The idea was elegant: On Earth, the planet's gravitational field obscures the minuscule gravitational effects predicted by general relativity; but in space, highly sensitive gyroscopes could measure the effect unimpeded—presuming it was there.

Not long after drying off, the three swimmers sketched out an early version of what is now considered one of NASA's most interesting scientific experiments: Gravity Probe B. It took 32 years, the invention of new technologies, countless demonstrations to highly skeptical fellow scientists, and some intense lobbying of Congress, but at last NASA seems about to float Schiff's idea. It was cut from NASA's budget four times, but now the $300-million project is funded at $27.2 million for fiscal year 1992, and a launch is scheduled for 1995 to test the technology on the space shuttle. That is to be followed by a full-fledged satellite mission in 1998. When it finally flies, the scientific payoff for the experiment, under the leadership of Francis Everitt, Bradford Parkinson, and John Turneaure of Stanford (Schiff and Fairbank are no longer alive) could be enormous, because almost all the deepest speculations of modern cosmology—such as those describing the expansion of the universe and the behavior of massive black holes and neutron stars—draw on Einstein's theory of general relativity.

Schiff had been pondering the shortcomings of existing tests of this theory for years, but there was no means to test it in space until the early 1960s, when the newborn NASA began plans for its first Orbiting Astronomical Observatory (OAO). in 1963 the Stanford team made its first pitch to NASA for money—and it hoped to fly its experiment on the OAO. NASA came through with research money but made it clear from the start that it thought the experiment was a long shot, recalls Cannon. "Many of us didn't believe they could do it," says University of Chicago physics professor Eugene Parker, who reviewed the proposal for NASA in the late 1960s. "We thought it was very clever, but we were skeptical that anyone could devise a way to measure such a tiny effect."

Yet over the years the Stanford researchers have leaped over one technological hurdle after another, so that by now their far-fetched idea has gained so much momentum that it will be hard to stop. And most reviewers find the experiment alluring because it takes on aspects of general relativity that previously have been virtually impossible to test directly. Although important progress has been made in the past 30 years to confirm parts of the theory, there are still large holes—and Gravity Probe B's verdict—pro or con—could reverberate throughout all of physics and cosmology. As Irwin Shapiro, director of the Harvard-Smithsonian Center for Astrophysics (CfA), put it in a letter to NASA in 1989: "Gravity Probe B is widely recognized as the most important (fundamental) physics experiment NASA has ever undertaken."

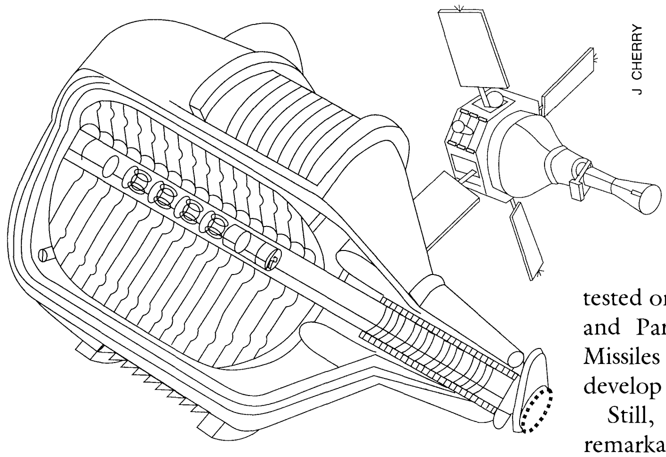
But therein lies an exquisite irony. Gravity Probe B is just the kind of moderately priced, cutting-edge scientific experiment NASA claims it wants to fly in space. And yet because it is an oddball that fails to fit in with the agency's usual astronomy mission goals and because it is competing for scarce resources, NASA administrators have tried to kill the project twice since 1980. But along the way the Stanford researchers have kept the project alive by finding a few key friends inside NASA and Congress, and by acquiring the skills of lobbyists and bureaucratic maneuverers.

It didn't hurt that their experiment offers the romance of testing the ideas of not just one but two great luminaries of physics—Einstein and Newton, whose theories on gravity disagree in important ways. Newton said in his time-honored theory of the universe that gravity is a force transmitted instantaneously over vast distances—a notion challenged by Einstein when he worked out his famous theory of special relativity in 1905, which says that no signal can travel faster than the speed of light. It then follows that gravity could not be a force that travels out from a massive object to tug instantly on everything around it. So Einstein proposed instead in 1916 that gravity is not a force but a "field" that warps space and time (also known as space-time, the continuum in Einstein's four-dimensional universe where time is the fourth dimension). Massive objects, such as the sun, curve the fabric of space-time around themselves as they move, much as a human cannonball dimples a safety net. Seen that way, the planets don't orbit the sun because a gravitational force holds them onto elliptical paths (as Newton predicted). Instead, each planet travels along a straight line (a geodesic), but its path is elliptical because it is moving in curved space.

Although several critical aspects of the theory remain untested, it appeals to cosmologists because it is the most elegant way to explain the behavior of many massive objects moving at velocities close to the speed of light. General relativity is used, for example, to explain the way black holes and active galactic nuclei warp space around them, and the way light is bent as it travels through large gravitational fields. "There's no issue of the *Astrophysical Journal* that goes by without an implicit reliance on the theory of general relativity," says Stuart Shapiro, a theoretical physicist at Cornell University whose specialty is general relativity, and who is a strong backer of Gravity Probe B.

Yet it has always nettled those who rely on the theory that it has been so difficult to test. Einstein himself could think of only a couple of small effects to test, such as observing the way Mercury's orbit precesses as it spins around the sun—gradually turning in its plane through an angle minutely different from Newton's prediction. Stars observed near the edge of the sun should appear slightly displaced outward, while light leaving a star should change color subtly, shifting toward the red. By now, these effects have been largely confirmed, yet not everyone is willing to conclude from this success that Einstein was therefore entirely right. In fact, physicists such as Nobel laureate C.N. Yang have predicted that Einstein's theory will break down at some point, partly because the mathematical structures for it and quantum mechanics seem utterly incompatible. One place to start looking for such a breakdown is to search for some of the more profound phenomena described by general relativity: For example, no one has directly observed the existence of gravitational radiation—the undetected waves of energy that travel through space, exerting gravitational forces on any mass in their path.

Even less is known about another phenomenon predicted by general relativity: frame dragging. This notion holds that a rotating massive body, such as a black hole or Earth, slowly drags space-time with it as it spins. It was just this concept that particularly interested Schiff. The Stanford researchers realized they could line up gyros on a distant star and then see if Earth's rotation would drag space and time around with it and alter the direction of the gyros' spin. If Newton was right, the gyroscopes should stay aligned on the star forever—because there would be no effect of the spinning Earth. But if Einstein was right, Earth's rotation should drag space-time along with it, subtly altering the gyros' direction of spin over time. Schiff calculated that the instruments should be pulled out of alignment by a tiny angle of 42 milliarcseconds a year; Gravity Probe B aims to measure this change in spin to a precision of 1% or better.



J CHERRY

Gravity probe thermos. *Four gyros and a telescope will fly in a chilled satellite.*

To give you an idea of just how precise this angle is, it's like trying to see a fraction of the width of a human hair from 10 miles away. Which is why the main challenge that Gravity Probe B had to overcome over these last 30 years was for scientists and engineers to develop no less than four near-perfect gyroscopes that could do their job suspended in mid-air in a near-perfect vacuum at near-zero temperatures in near-zero-gravity in a near-zero magnetic field. All that effort is designed to protect the gyros from disturbances that could accidentally alter their spin: vibrations from the satellite, drag as the vehicle moves through tenuous gases, or accelerations caused by changes in solar radiation pressure.

Furthermore the satellite, which will have its position fixed by a telescope set on the guide star Rigel, 300,000 light-years away, will have to sense when the unmarked gyros' spin changes ever so slightly—and communicate that precise information back to Earth. Finally, there has to be a calibration system to make sure the instrument is free from errors that might masquerade as a relativity signal. No wonder Parker says, "This is a technical tour de force."

With Schiff as a senior adviser (until his death in 1971) Fairbank, Cannon, and Everitt put their heads together and also enlisted the help of other faculty and students at Stanford. The team came up with a closetful of technical wizardry: the world's roundest gyroscopes, a drag-free satellite, a refrigerated capsule capable of holding superfluid helium in place and cool for 2 years, and a method for detecting the change in gyro spin with superconducting technology. By 1984 NASA had decided the experiment should be tested on the shuttle, and Everitt and Parker selected Lockheed Missiles & Space Co. to help them develop the flight instrument.

Still, in the very face of this remarkable technical innovation, there has been a residual skepticism at NASA. The agency sent team after team to Stanford to examine the project—with many of those teams beginning as skeptics. Yet they all wound up recommending that the project go ahead. "Some of the best experimentalists have tried, but they haven't been able to poke a hole in it," says Shapiro, director of the CfA. "In the 25 years since I first reviewed it, Everitt and associates have showed that, by golly, it could be pulled off—if you're as clever as they are," adds University of Chicago physicist Parker. And for that reason, Parker's committee recommended this spring that NASA go ahead with the mission—but that it continue to leave the experiment in the hands of the team at Stanford. "It must be done precisely properly," says Parker. "If you put it in the hands of someone who is not as finely tuned, it probably won't work."

It may be a sign of the times, but in spite of such ringing scientific endorsements Gravity Probe B has barely escaped the budget-cutting knife. In fact, NASA and the Office of Management and Budget have separately axed the project in 1980, 1985, and 1990. The Senate Appropriations Committee also almost cut it this past August. Why would they cut this effort? NASA deputy administrator James R. Thompson—who says he would like to see it fly—concedes that it is an "elegant piece of science" but adds the usual explanation: Severe budgetary pressures caused the agency to make painful choices among an array of top science missions.

And in that kind of bureaucratic bloodletting, Gravity Probe B was likely to come out as a lower priority because it is "a sort of stand-alone thing," says Thompson, that doesn't fit in the usual mission categories, such as astronomy, observing platforms, or life sciences. Furthermore, Thompson says, it "doesn't have the broad constituency that the astronomy missions do"—meaning the experiment will be built and used by only one university, not many, as some projects are.

Despite these hammer blows, Everitt always revived his project, partly with the help of NASA insiders such as Charles Pellerin (head of astrophysics and physics) and researchers at NASA's Marshall Space Flight Center. "I did what people usually do after they've been zeroed. You learn to lobby," he says. Two congressional aides gave Everitt and Fairbank a crash course, and they took to the halls of Congress—learning to peddle the romance of Einstein, the glamour of high tech, and the value of educating students (the project has produced 33 Ph.D.s). Stanford even published a glossy 28-page brochure on the experiment.

The work paid off each time when Congress restored Gravity Probe B to NASA's budget. By now the project "has significant congressional support," says a staff member of the Senate Appropriations Committee. "It's good science, it's affordably priced, and it's not the kind of science that NASA usually supports. We think it would be a real tragedy to cut it." Obviously, so would the researchers at Stanford, more than one of whom has made it his life's work. "If I had known how long it would take when I started this at age 28, I would have thought I was a fool to have gotten into it," admits Everitt. But as Gravity Probe B stands now—with NASA funding, a launch date, and an enviable technological track record—Everitt can still add, "I'm delighted that I did." ■ ANN GIBBONS

AIDS: The Evolution of an Infection

AIDS researchers have long been puzzled by the prolonged clinical course of the disease: A person infected with HIV can apparently combat the virus for more than a decade, and then his or her immune defenses give out, opening the door to an onslaught of opportunistic infections, and, in most cases, death. Some investigators have insisted that a cofactor—possibly another infectious agent such as a mycoplasm—must be involved. Others have speculated that the AIDS virus may become more pathogenic as it replicates inside the infected host.

But now a team of researchers in England and the Netherlands has come up with a radically different explanation of what happens during the years that the immune system is under assault by HIV. They suggest, in an article on p. 963 of this issue of *Science*, that the progression to disease can be viewed as an evolutionary process with a timescale measured in years rather than millennia. And they have developed a mathematical model that not only describes the clinical course of the disease but also raises doubts about some of the strategies being used to develop vaccines or drug therapies against HIV. While virologists who have seen the model are intrigued, they are generally skeptical because so far it is supported by scant experimental evidence: Only two patients' infections are chronicled in the *Science* paper.

Martin A. Nowak, a mathematical biologist working with population biologists Roy M. Anderson and Robert M. May at the University of Oxford department of zoology, first sketched out the hypothesis last year in the journal *AIDS* (vol. 4, p. 995). It is based on a biological property that HIV shares with all retroviruses: It lacks any mechanisms to correct errors that occur when its genetic material is being duplicated. This means that every time the virus makes a copy of itself there will be, on average, at least one genetic "mistake" incorporated in the new virus. So a few days or weeks after initial infection, there may be a large population of closely related, but not identical, viruses replicating in an infected individual. While the immune system will recognize most members of this population of viruses, some mutants will evade the immune response for a time. Until they are brought under immune control, these so-called escape mutants will attack a class of T cells that express a receptor called CD4. It is these CD4 cells that are key to orchestrating the overall immune response, and once they are gone the immune system collapses.

As the virus grows and continues to produce mutant forms, the immune system and responds to these new forms. But ultimately, Nowak and his colleagues conclude, the sheer number of different viruses to which the immune system must respond becomes overwhelming. It's a bit like the juggler who tries to keep one too many balls in the air: The result is disastrous. Once the immune system is overwhelmed, the latest escape mutant—which may not necessarily be the most pathogenic one to come along—will predominate.

Once they had worked out their model on paper the Oxford group, along with Tom F. W. Wolfs and Jaap Goudsmit of the Human Retrovirus Laboratory in Amsterdam, looked at the pattern of viral diversity in two HIV-infected patients to see whether they had accurately predicted the course of the disease. Both patients first developed antibodies to HIV in 1985. One man, who developed AIDS, did show a rapid decline of the number of different HIV quasispecies after AIDS symptoms began to appear. For the other, who remained asymptomatic over the duration of the study, the diversity continued to grow.

More studies of this kind will be needed to convince other AIDS researchers that the model is valid. "This is a reasonable hypothesis," says virologist Harold Burger of the New York State Health Department's Wadsworth Center for Research, "but it is important to get an adequate amount of data to confirm it." Gerald Myers, who studies viral diversity at Los Alamos National Laboratory, is more skeptical. He thinks that the decline in viral diversity in the one patient presented in Nowak's paper is an artifact that is explained by that patient's use of the antiviral drugs DDI and AZT. But Myers agrees with Nowak and his colleagues that the model raises some interesting questions for future research.

For example, if a vaccine is targeted against a particular strain of the virus—say one that has stabilized after years of growing in culture—will it be effective against a constantly diversifying virus population? Nowak's model suggests it won't. The same goes for therapies that try to enhance the ability of the immune system to respond to the virus. If the therapy is begun after there is already a lot of viral diversity, these therapies will not be effective. On the other hand, a therapy that will slow viral diversity early in the course of infection—such as DDI and AZT appear capable of doing—could delay the onset of symptoms by years.

For now, the search is on for more data to validate—or invalidate—the model. Myers thinks these data may already exist in labs that have been looking into the change in the virus during an infection. If so, Nowak and his colleagues won't have long to wait to see whether their novel mathematical model accurately reflects the real world. ■ JOSEPH PALCA