Gravity
THE PROBE

If Einstein was right, a spinning planet should twist the fabric of space-time. To see the effect, all we need is a perfect gyroscope. And a perfect telescope. And a perfect vacuum in a perfect chamber in an orbit 400 miles up. After 40 years of planning and half a billion dollars, the test is about to begin.

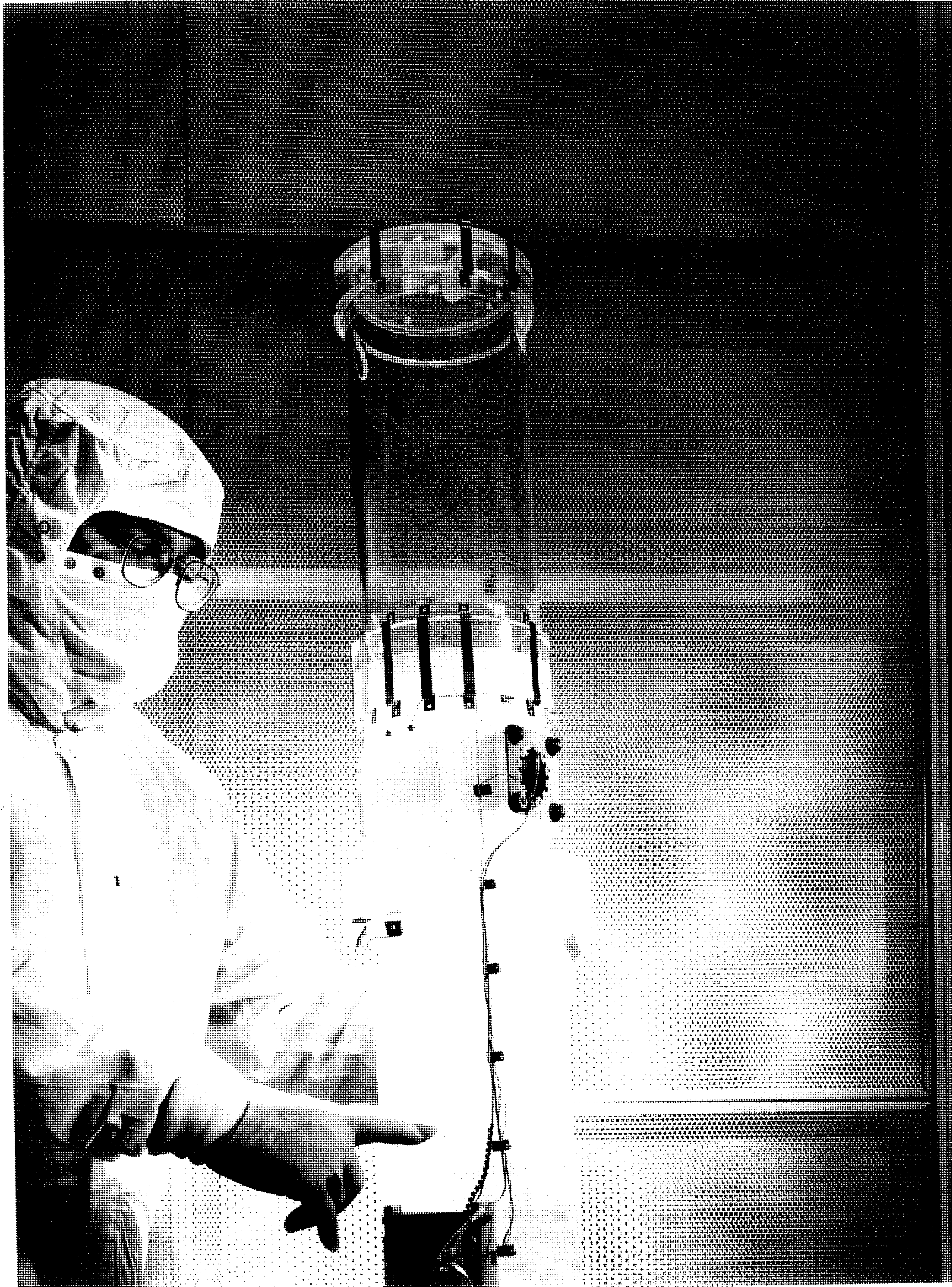
BY GARY TAUBES

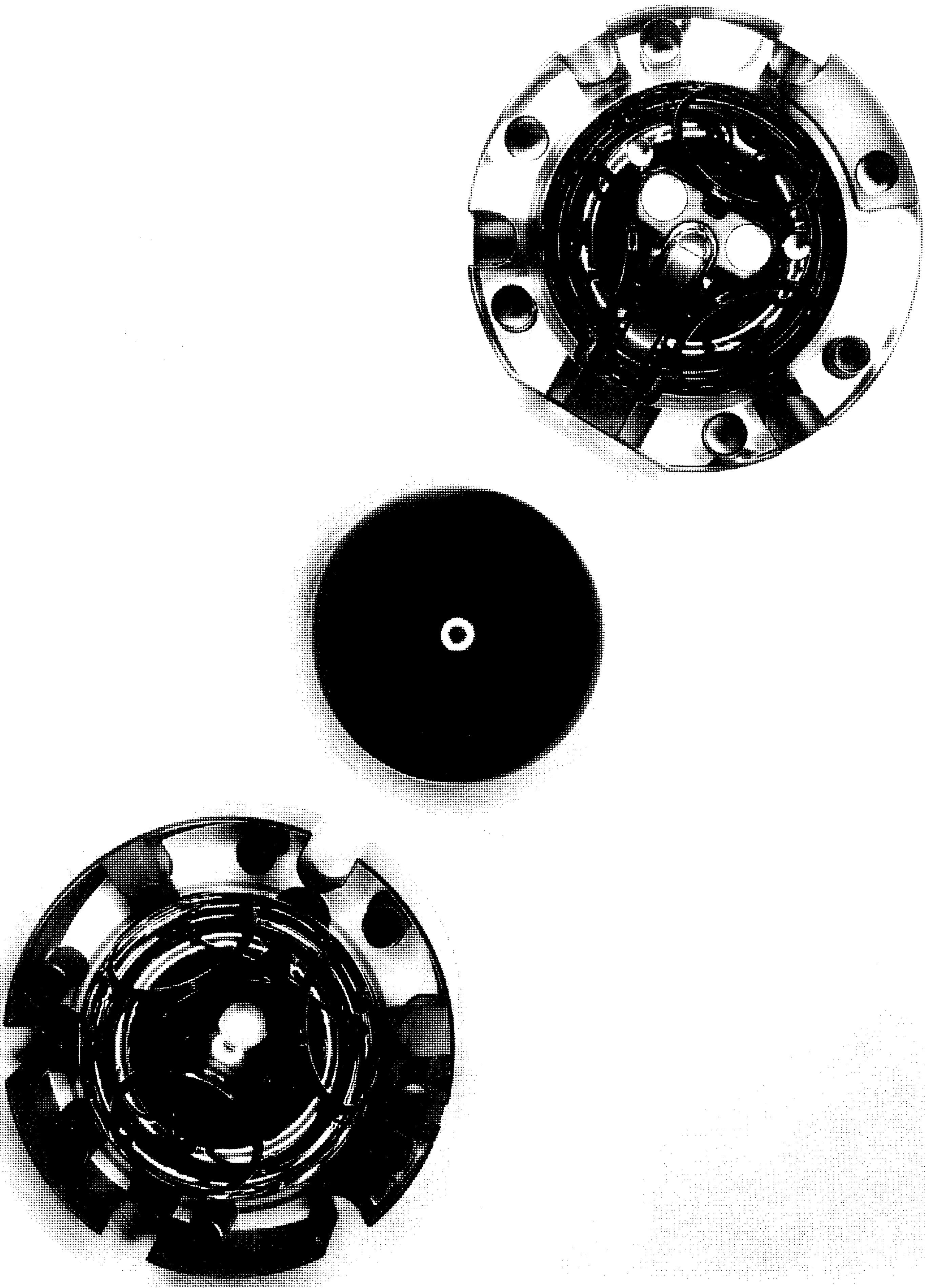
PHOTOGRAPHS BY DAN WINTERS

IN LATE 1959 LEONARD SCHIFF, THEN A PROFESSOR OF PHYSICS AT STANFORD, NOTICED A MAGAZINE ad for a new kind of gyroscope. The ad prompted a discussion with his colleague William Fairbank, an aficionado of low-temperature physics, who asked what he would do with a perfect gyroscope, should such a device ever be constructed.

Schiff's answer was just what Fairbank had in mind himself: Use it to test Einstein's general theory of relativity. In particular, test one of the theory's more remarkable predictions—that a rotating body in space would pull the very essence of space-time around with it. The effect, known as frame-dragging, would be small enough to serve as a pedagogical illustration of the word *infinitesimal*, but it should exist. And it would take a close to perfect gyroscope to observe it.

A PHYSICIST VISITS THE PROBE'S SCIENCE INSTRUMENT IN A STANFORD CLEAN ROOM. THE STRUCTURE WILL HOLD THE TELESCOPE AND GYROSCOPES.





In 1960, Fairbank, Schiff, and Robert Cannon, a Stanford engineer, took this idea and initiated the Stanford Gyroscope Experiment, as they it called at the time. According to local legend, the three were dripping wet when they made their decision; Francis Everitt, the Stanford physicist who has been heading the project since 1971, calls this "the famous story you've heard ad nauseam about the swimming pool and the three naked men." In the pool, they also agreed that if they wanted the gyroscope to be perfect, they would have to put it in a satellite and send the satellite into orbit.

Thirty-seven years later, what began as a seemingly rhetorical question has grown into NASA's longest running astrophysical development program. Gravity Probe B, as it's now called (Gravity Probe A was a 1976 experiment that tested another aspect of relativity), first found support from NASA in November 1963 and has been proceeding not quite apace ever since. Over the years, a series of NASA-instituted review boards have applauded the program for its remarkable technological accomplishments. In the 1980s it was even designated the centerpiece for the agency's gravitational physics program. Yet it has also been canceled, so far, seven times. As of today, Gravity Probe B is scheduled to be launched into orbit some time between December 1999 and October 2000, a mere four decades after its conception.

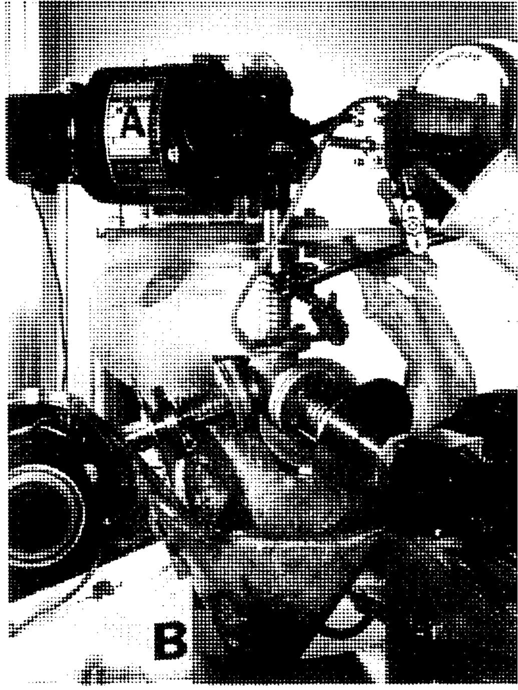
Forty years may seem like an extended gestation period for a single experiment. But if nothing else, Gravity Probe B will perform the most accurate confirmation ever of Einstein's theory of relativity, and that alone, its proponents insist, would make the mission worth the investment. Then again, it's possible that the probe will measure a phenomenon quantitatively different from the prediction of general relativity. If so, says Everitt, who seems fond of rating physics discoveries on a scale of one to ten, "that would probably be a nine or a ten." But, he adds, "let's not second-guess what Gravity Probe B is going to do."

The study of general relativity has become something of an anachronism in physics. The theory is so deeply rooted in our science and culture that those who study it sometimes seem to have left physics for philosophy. In the universe as Einstein saw it, which he called the four-dimensional space-time, nothing was absolute. The geometry of space would act on matter, telling it how to move. In turn, the presence of matter or energy—the two are equivalent in an Einsteinian universe—would act on space, telling *it* how to curve. Gravity was no longer a mysterious force acting at a distance but the result of an object trying to travel in a straight line through space curved by the presence of material bodies.

Not only was general relativity conceptually beautiful, but it was checked and confirmed quickly. Among Einstein's predictions was that light from a distant star would appear to bend inward as it passed through the gravitational well of the sun, and therefore when Earth, the sun, and the star were lined up, the star's image would appear to have moved outward from its normal position. All that was needed for the experiment was a good camera and a solar eclipse, which would line up the three bodies while allowing the star to be seen. When nature provided the latter on May 29, 1919, photographs confirmed that we lived in a curved four-dimensional space-time.

SINCE THEN, SPATIAL CURVATURE has been tested and confirmed to greater and greater accuracy, giving physicists enormous faith in the general theory of relativity—but not necessarily absolute faith. "The very fact that Einstein was so successful has a tendency to make people shrink from saying something may be not right," says C. N. Yang, a Nobel Prize–winning physicist at the State University of New York at Stony Brook. "But science progresses precisely by finding fault with what has already been accepted." And, surprisingly, the curvature of space-time in its various manifestations is the only direct effect of general relativity that has ever been tested. Frame-dragging, which can be considered a distinct phenomenon entirely, if not a completely new kind of force, has never been measured or observed directly.

In 1918, two years after Einstein formulated his theory and the year before the eclipse that confirmed it, two Austrian physicists, Josef Lense and Hans Thirring, calculated that as a natural consequence of Einstein's theory, a massive body spinning in space would drag space and time around with it. To explain precisely why this is so is difficult, but four decades ago, when Leonard Schiff took to thinking about the effect, he suggested a purely intuitive illustration: Imagine Earth immersed in a viscous fluid, he said, like molasses. Spin the planet, and the molasses, depending on just how viscous it is, will be pulled around with it. Any object in the molasses will be pulled around as well. This frame-dragging effect should be most noticeable close to the rotating Earth, and should eventually fade to virtually nothing farther away.



THIS INSTRUMENT POLISHES THE INCH-AND-A-HALF-WIDE ROTORS UNTIL THEY ARE WITHIN 50 ATOMIC LAYERS OF BEING PERFECT SPHERES.

Measuring such an effect is where the perfect gyroscope comes in. Gyroscopes have been around since the early 1850s, when French physicist Jean-Bernard-Léon Foucault invented them to demonstrate that Earth rotated. (Foucault's more famous pendulum served the same purpose.) A gyroscope is little more than a flywheel—a bicycle wheel, for instance—that spins around an axis. But once the wheel is set spinning, the axis of the gyroscope will keep pointing in the same direction as long as no other force comes along to reorient it. This effect depends on a principle of physics known as

THE GYROSCOPE ROTOR, A NIOBIUM-COATED QUARTZ SPHERE, WILL WHIRL BETWEEN TWO CUPS, ONE TO PUSH IT AND ONE TO MEASURE ITS SPIN.

THE GYROSCOPES HAVE BECOME THE GROUP'S ADVERTISING COUP. WHEN YOU'VE MADE PROBABLY THE MOST SPHERICAL OBJECTS IN THE KNOWN UNIVERSE, YOU ARE GOING TO GET ATTENTION.

the conservation of angular momentum, which explains why, for instance, it's easy to sit upright on a bicycle when it's rolling along and the wheels are spinning, and much, much harder to do so when it's at rest.

As Schiff figured it, the way to measure frame-dragging would be to take a perfect gyroscope—one that would continue to spin and point in the same direction effectively forever—and send it into space. This gyroscope could be set spinning with its axis pointing at some distant object whose position in the universe appeared fixed—a star, for instance. If the gyroscope was sufficiently close to perfection and frame-dragging was just a figment of Einstein's imagination, then the gyroscope would go on pointing at its chosen star for eternity. But if frame-dragging existed, the gyroscope would keep pointing in the same direction with respect to local space-time, but that local space-time would be dragging along with Earth. As a result, the axis of the gyroscope would slowly begin to slip off its alignment with the star. Or, as Everitt puts it, "the star is providing a reference to what space is doing out there, and the gyroscope is affected by what space is doing right down here. And if we line up our gyroscope on a distant star, it is not necessarily going to stay lined up on that star."

The effect is like that of a sundial. We cannot feel Earth's rotation, but if we align a sundial with a relatively fixed object like the sun, it will soon become obvious that one of the two is moving. Unlike the rotation of Earth, however, frame-dragging is an infinitesimal phenomenon.

Suppose a perfect gyroscope were put into orbit 400 miles up, where it would be beyond most other Earthly disturbances. As Schiff figured, frame-dragging would skew the gyroscope from its original orientation by some 42 thousandths of an arc second (or seven ten-thousandths of a degree) each year. That's not much. A thousandth of an arc second is the perceived width of a human hair when viewed from ten miles away, which means that 42 milli-arc seconds is the width of a single human hair seen from a quarter mile away.

With this in mind, the Gravity Probe B experiment can be thought of as two coupled pointers that orbit Earth together. On the one hand is a telescope that will set its sights on the distant star and keep pointing at it no matter what. On the other are the perfect gyroscopes, in this case four of them, which will initially be aligned on that distant star as well. As local space drags after Earth, however, the gyroscopes should drag with it, while computers and excruciatingly gentle thrusters on the satellite will keep the telescope pointing at the star. Given time, the misalignment between telescope and gyroscopes should become big enough to measure—if just barely.

THAT THE CHANGE IN ALIGNMENT over the course of a year will add up to less than the width of a human hair explains much of what the Stanford scientists have been doing for the past few decades. They have had to develop not only near-perfect gyroscopes but a near-perfect environment in which to spin them, and a near-perfect telescope and guidance system to keep that telescope lined up on a suitably distant star. The Gravity Probe B crew like to boast that their success at creating a "near-zero environment"—no gravitational acceleration (other than perhaps frame-dragging), no atmosphere, no magnetic field, no electric field, no nothing—will give them a measuring device of extraordinary sensitivity. "There is no substitute for lots of sensitivity," says Everitt, defining the philosophy of the program.

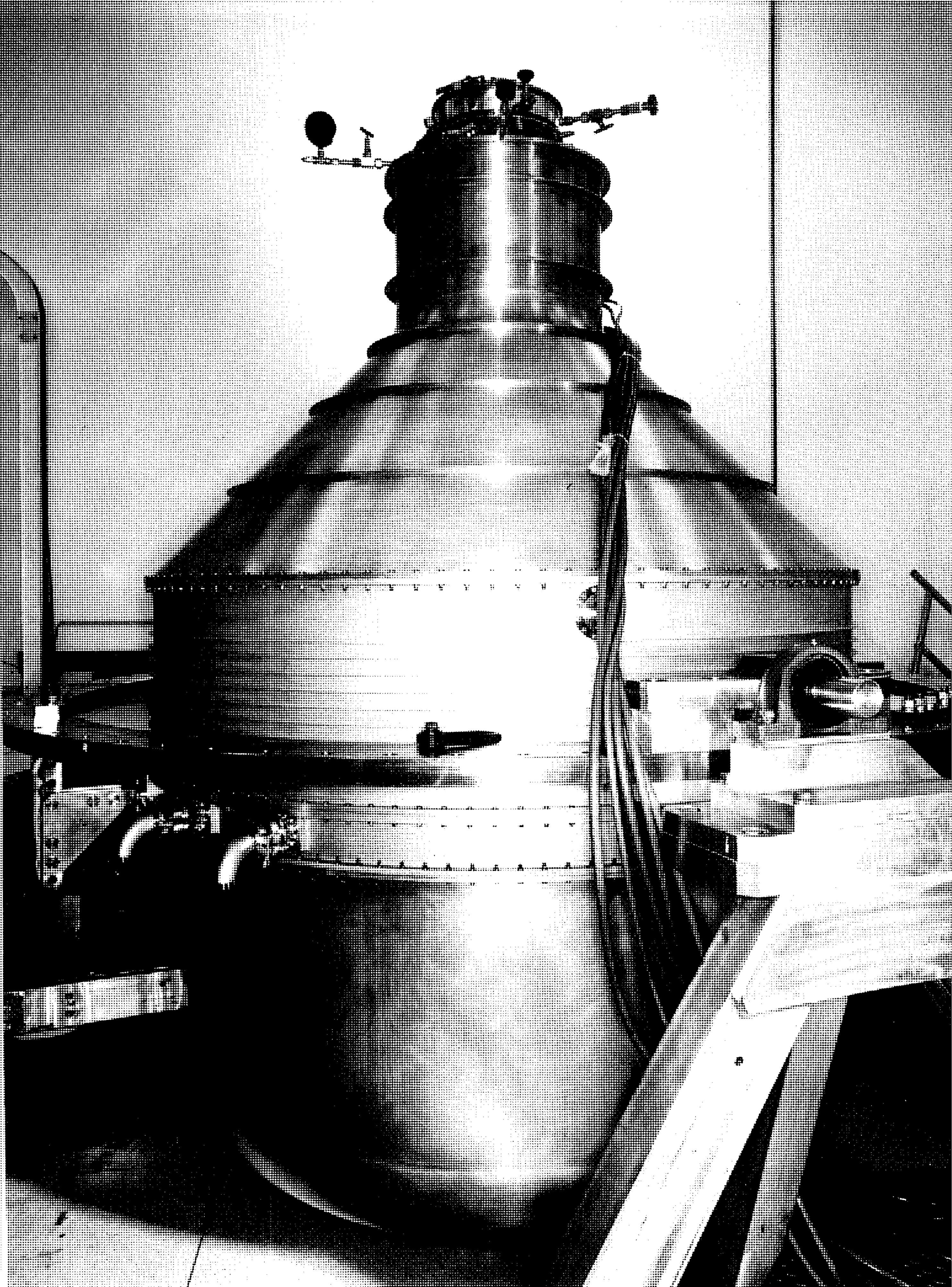
The four gyroscopes have become their advertising coup. When you've made probably the most spherical objects in the known universe (outside of astronomical phenomena known as neutron stars and discounting, of course, the possible products of extraterrestrial gyroscope makers), you are going to get attention. After all this time, says Everitt, making the gyroscopes turned out to be straightforward. By that he means "difficult but straightforward."

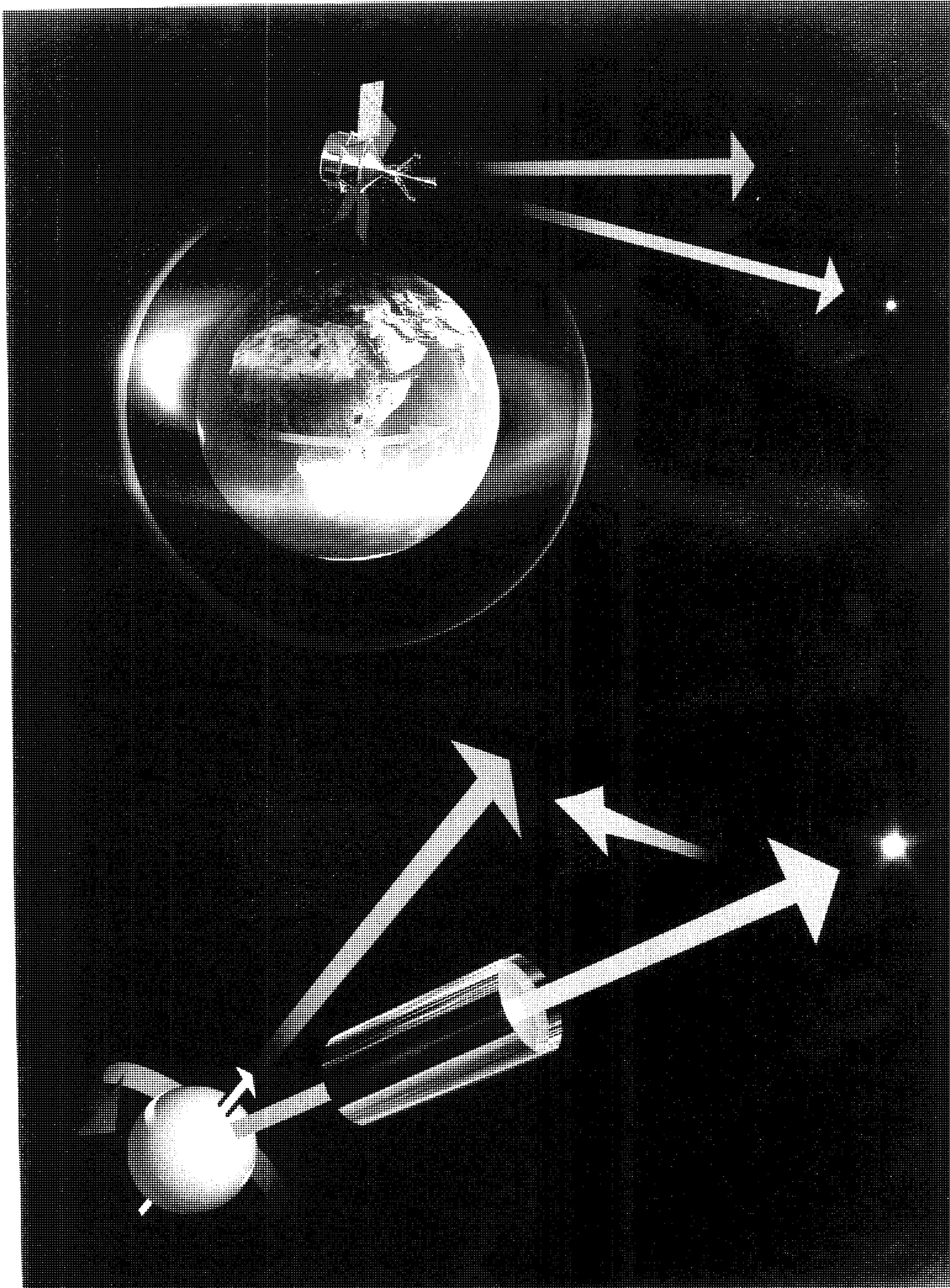
The rotors—the spinning part of the gyroscope—are a triumph of sphericity. Quartz globes one and a half inches in diameter, coated with a layer of niobium, they look like idealized silver squash balls. They have been lapped and polished to within 50 atomic layers of being perfect spheres. The deviation between their highest and lowest points is less than one-millionth of an inch. And as anyone associated with Gravity Probe B will gladly remind you, if Earth were correspondingly round, the highest mountain would tower all of 20 feet over the depths of the deepest ocean trench.

Perfection, however, comes with inherent complications. For instance, how do you mount and spin a near-perfect ball without ruining the symmetry? And how do you tell in which direction its axis is pointing when you've gone to so much trouble to make it exactly spherical—and therefore unmarked?

Both of these problems are solved by the electrical properties of the niobium coating the rotors. Niobium is a superconductor, which means that if cooled to a few degrees above absolute zero (-459.67 degrees Fahrenheit), it will lose all resistance to electricity, and an electric cur-

THE FLIGHT DEWAR—ESSENTIALLY A NINE-FOOT THERMOS—WILL HOLD THE INSTRUMENTS, ALONG WITH 2,300 LITERS OF LIQUID-HELIUM COOLANT.





rent, once incited, will run around it endlessly. The researchers will mount the rotors in spherical cavities, with a thousandth of an inch of clearance for the rotor to spin freely. Inside the cavities are three pairs of titanium-coated copper electrodes. An electric charge will be applied to the electrodes, which will then repel the niobium on the rotors and levitate them. Once they're up, a stream of helium gas will be squirted through a channel, setting the rotors spinning at some 10,000 revolutions per minute. As soon as they're going, the remaining gas will be pumped out, and the gyroscopes, now in a near-perfect vacuum, could theoretically go on whirling for a good hundred thousand years, if the coolant supply held out that long, which it won't. The probe is expected to exhaust its coolant in just two years.

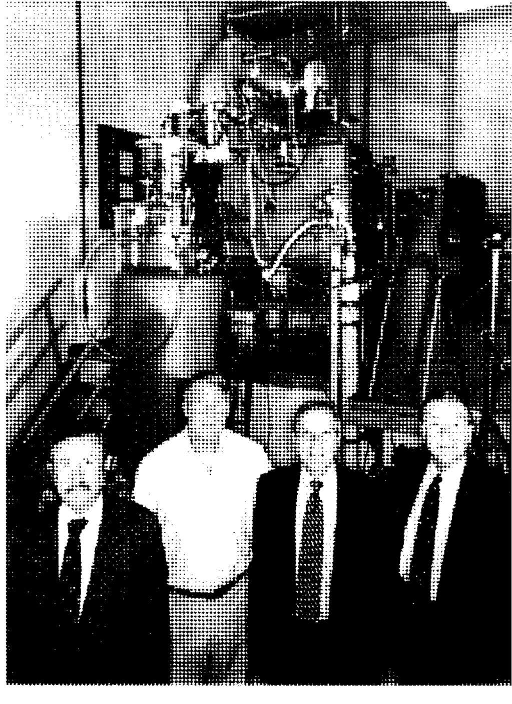
THE PROBLEM OF DETERMINING the direction of spin turned out to have been solved theoretically back in the 1930s by Fritz London, a German-born physicist working in England. London predicted that a spinning superconductor, unlike any normal metal, would create its own magnetic field and that the north-south axis of this field would be exactly aligned with the axis of the spinning superconductor. In a spinning superconductor, London suggested, the electrons in the metal would rotate slightly more slowly than the positively charged particles, and the rotating electric charge that resulted would create the magnetic field. (Because the electrical resistance in a normal metal causes the electrons to spin along with the rest of the positive charges in the metal, there is no rotating charge and thus no magnetic field.) Fairbank himself discovered in 1963 that this London moment, as it's called, actually exists and suggested using it as a marker. "Without that, we're dealing with an unmarked ball," says Brad Parkinson, an engineer and former Air Force colonel who is one of the program's three co-principal investigators. "The bad news, however, is that the London moment is fairly weak."

To detect London moments, the Gravity Probe will have to be outfitted with four superconducting quantum interference devices, or SQUIDs, one for each gyroscope. This extraordinarily sensitive tool will measure the magnetic fields and should detect any changes in the direction of the London moment, and therefore in the spin direction of the rotors. The SQUIDs are so sensitive that in five hours they can measure the orientation of the London moment to a thousandth of an arc second. (By launch, Everitt hopes to have that read-out time down to even fewer hours. "Straightforward," predicts Everitt. Well, difficult but straightforward.)

The Gravity Probe B gyroscopes will eventually be mounted in a solid quartz structure that includes the telescope designed to keep the probe fixed on a distant star. This structure will then be placed within a nine-foot-long dewar—essentially a big thermos—filled with 2,300 liters of liquid helium, which will cool the device to 2 degrees above absolute zero and last through the mission's 20-month duration. The low temperature will keep the probe's quartz housing stable and keep the superconductors cold enough to superconduct.

Before the probe goes in, however, any magnetic field in the dewar will have to be pumped out by inserting a succession of lead bags into the container and inflating them one after another. This was another of Fairbank's ideas back in 1963. At low enough temperatures, lead can be a superconductor as well, and another remarkable property of superconductors is that magnetic fields cannot pass through them. "As you expand the lead bag so that it has a larger interior volume, any magnetic flux that is trapped in the bag has to expand over a larger volume, so the field strength has to go down," explains Stanford physicist John Turneaure. "It's a little bit like if you take a cubic centimeter of water and expand it into a thousand cubic centimeters volume. It's going to be considerably less dense." By the time four or five lead bags have been inserted and inflated, and the probe set into the dewar, the magnetic field left around the gyroscopes will have been diluted by a factor of 10 million or so.

The gyroscopes also have to avoid virtually all external acceleration, which is not as easy as it sounds. (When astronauts talk about zero-g, the *g* stands for gravity, but what they're really talking



LEFT TO RIGHT: FRANCIS EVERITT, JOHN TURNEAURE, BRAD PARKINSON, AND ROBERT CANNON, WHO HAS WORKED ON THE PROJECT FOR 37 YEARS.

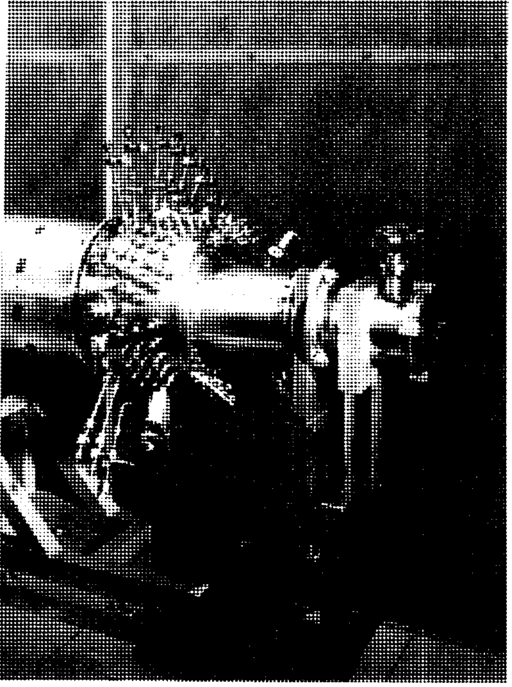
about is an environment free of gravitational acceleration. While gravitational forces exist everywhere in the universe, in a zero-g environment like the space shuttle, Earth's gravity is pulling the shuttle and everything inside it around Earth but not toward it, therefore gravity goes unnoticed and its force appears to be nearly zero.) Although Gravity Probe B will be in zero-g by astronaut standards once it reaches its orbit, it will still be buffeted not only by solar wind but by Earth's magnetic field and the upper part of the atmosphere.

"We want to fly as low as we can," says astronautical engineer Gaylord Green, who is in charge of the mission's spacecraft, "because we get our best [frame-dragging] signature there, but we have to fly high enough so that we're above the atmosphere. So we fly right at the upper fringes of the atmosphere, and where the atmosphere itself turns into space it's almost like ocean tops, little waves and sprinkles of molecules, that will keep hitting the satellite." The constant acceleration and deceleration that results would be unacceptably large for an experiment designed to measure a nearly infinitesimal effect.

The solution is to build Gravity Probe B as a drag-free satellite, a concept that

ONCE THE ORBITING PROBE IS FIXED ON A STAR, WILL EARTH'S SPIN WARP SPACE AND PULL THE GYROSCOPES OUT OF ALIGNMENT WITH THE TELESCOPE?

ILLUSTRATIONS (OPPOSITE) BY DANA BERRY



AN ARRAY OF VALVES LET IN HELIUM GAS TO SET THE GYROSCOPE ROTORS SPINNING.

physicist Ben Lange helped develop in the 1960s as his doctoral thesis at Stanford. As Lange explains it, the researchers enlist one of their four gyroscopes to act as a proof-mass, an object allowed to fall freely around Earth within its near-perfect environment. In effect it is allowed to respond to the local gravitational field without any outside disturbances. As it does so, devices called capacitance sensors check on its position with respect to the surrounding satellite. These sensors then tell the satellite's thrusters which direction to push the satellite to keep it centered around the mass. Although, as Green says, the word *thruster* is something of a misnomer. The satellite uses as its thrust the minuscule amount of helium gas that slowly boils out of the dewar to cool it, just the way evaporating sweat cools you down. "What we do is take the gas from the helium dewar," says Green, "sort of like a very gentle breath, and that's the gas we use to control the satellite. As a result, we're nearly seven orders of magnitude closer to zero-g than when astronauts float around in the space shuttle."

Once in orbit, the telescope on the probe, which is all of 13 inches long, will keep the satellite aligned on a distant star to within 20 milli–arc seconds. When Everitt gives a tour of the Gravity Probe B facility, he points out the telescope testing room, where the researchers have built what they call an artificial star to practice tracking. "One learns from this device," Everitt says, "an extremely healthy respect for a thousandth of an arc second." It seems that the solid ground is not so solid after all. It tends to vibrate naturally, shaking the telescope by 20 milli–arc seconds and making the testing considerably more difficult.

Nothing's simple on Gravity Probe B, not even selecting a guide star. "You want a reasonably bright star that you can track," explains Parkinson. "Bright and blue, preferably. You don't want a lot of infrared light, because it will heat the experiment up. You don't want it located too close to the plane of the solar system or the sun will cross the telescope's path and burn its eyes out. You would like it to be somewhere near the plane of the equator, because if not, you have difficulty picking out the frame-dragging effect. If it's pointing toward the North Pole, you won't see it because you're pointing along the axis of frame-dragging rather than perpendicular to it."

They also want a star that isn't moving too much on its own. For instance, one with a large twin will wobble through space as the pair orbit around each other. If the star is also a radio source, the physicists could use its signal to measure its motion with respect to several strong radio sources known as quasars, which lie at the edges of the known universe. These quasars are too dim to track, but as radio sources they make ideal beacons with which to check the relative motion of potential guide stars. That way, the researchers can be assured that the star they choose is not going to botch the Gravity Probe experiment by wandering around the universe on its own.

IN THE EARLY 1990S EVERITT AND HIS colleagues engaged the Harvard-Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, to see if they could find a suitable candidate, which they figured would be easy considering how many stars there are to choose from. They were wrong, of course. It wasn't. It took the Harvard-Smithsonian researchers, led by Irwin Shapiro, several years to come up with all of two stars that fit the criteria—known by the astronomical designations HR-1099 and HR-8703, the latter also called Im Pegasi. ("That's in the constellation Pegasus," says Everitt, "and if you know the constellation Pegasus, you're a better man than I am, because I don't.")

Should the Gravity Probe B mission ever fly—"We think we've made most of our mistakes already," says Everitt, "or at least we hope we've made most of our mistakes"—it will perform the most precise test ever of any prediction of any aspect of general relativity. "That's clearly interesting," says Everitt. "The question is, is it more than interesting? And the answer to that is, we don't know." General relativity has become so well accepted and so well tested that there aren't any alternative theories to compete with it. On the other hand, because the force of gravity is so weak compared with the other forces of the universe—electromagnetism, for instance, which is 42 orders of magnitude stronger—physicists have been unable to test Einstein's theory with the same rigor that they've tested other favorite theories of the universe.

To make the test a little more interesting, frame-dragging and general relativity have cosmological implications ranging from the cataclysmic to the borderline metaphysical. On the cataclysmic side, for instance, are quasars. Take NGC 6251, which for the past 3 million years has been disgorging two monstrous jets of gas in opposite directions. The astrophysical engine at work here is generating the power of 1 trillion suns. And the prime candidate for such a generator is a supermassive black hole. But then there's another condition that the engine must fulfill: in NGC 6251, the jets of gas head straight outward, which means the source of these jets has remained pointed, unwavering, in the exact same direction for 3 million years.

"These compact objects must hold jet direction constant for times as long as 10 million years," says Kip Thorne, a gravity theorist at Caltech. "The only way a black hole can do this is by the gyroscopic action of its spin." In the most likely scenario, the black hole communicates the direction of its spin to the jet via frame-dragging. The frame-dragging pulls particles from near the black hole in a spiral toward the hole's rotational poles, then hurls them straight out in spectacular jets. None of this was known three decades ago, when Gravity Probe B was conceived. The experiment, says Thorne, has gone from one searching for a side effect of general relativity so infinitesimal "as to be interesting in principle but not in practice" to "a crucial test of a possible mechanism of the most violent explosions in our universe."

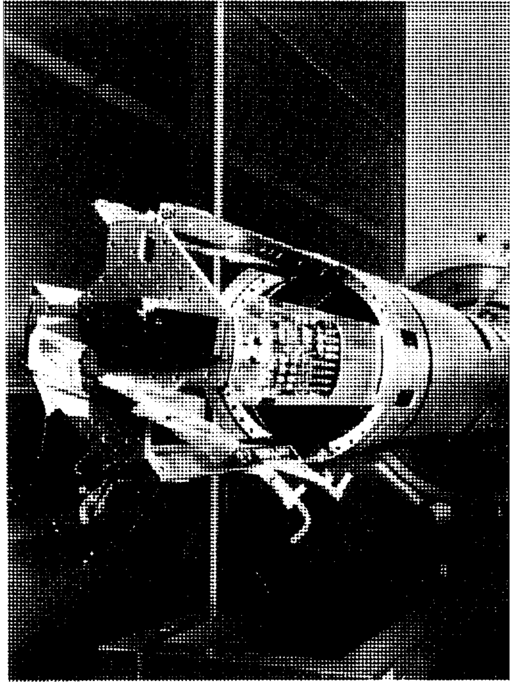
Then there's the near metaphysical implications of frame-dragging, which have to do with the concept of inertia, or a body's natural resistance to acceleration. (As Newton put it, a body in motion will remain in motion and a body at rest will remain at rest unless acted upon by an external force.) In particular, Gravity Probe B will test the proposition that the inertia of a massive body—Earth, for instance, or anything or anyone on it—is a consequence of the gravitational interaction, the frame-dragging, from all the other mass in the universe. In other words, says Everitt, "the stars out there create our inertia here." This concept is known as Mach's principle, after the great Austrian physicist Ernst Mach, who first proposed that the local properties of matter might originate in the properties of distant bodies.

Although Mach's principle has an astrological ring to it, it can be derived from a simple thought experiment. Imagine you are inside a massive spherical shell that is rotating around you in space—which, after all, is one way of looking at our actual situation. (You can think of Earth as rotating, but you can just as easily think of Earth as standing still while the rest of the universe rotates around it.) Now, with frame-dragging, the spherical shell very slightly pulls space and time around with it, which means you, too, will rotate slightly along with it. That's simple enough. Double the mass of the shell, and you double the frame-dragging effect. Now, consider that sphere getting more and more massive while simultaneously shrinking down around you until it's so dense, and the frame-dragging is so great, that as it rotates, you and your immediate universe will rotate right along with it. Now, the universe might conceivably *be* that massive; all the stars and galaxies and clusters of galaxies in the universe might really add up to so much mass that they serve the purpose of this supermassive rotating sphere. If so, we're all locked inside, with our inertia coming to us from the frame-dragging of all the distant stars.

To most physicists, inertia is a product of the masses of elementary particles, and those masses are determined by an esoteric concept known as the Higgs mechanism, which has nothing to do with gravity or general relativity. Since one of the goals of theoretical physicists is to find a single theory—known colloquially as a theory of everything—that uses a single, consistent set of mathematical equations to explain both the microscopic world of quantum physics and the macroscopic world of gravity, one way to go about connecting those two worlds would be to find out where inertia comes from. Does it come from the macroscopic world, the Einsteinian frame-dragging of the universe at large, or from the microscopic world of quantum physics? Since a potential theory of everything should resolve Mach's principle along with gravity and the quantum forces, an experiment, like Gravity Probe B, that can provide some insight may be helpful.

That does not mean, however, that everyone in the scientific community believes Gravity Probe B is worth the investment, which will eventually add up to more than half a billion dollars. Over the long years of the project, Everitt has become famous for working the congressmen and bureaucrats in Washington to keep his funding going, and some of his colleagues have accused him of selling his science to Washington before he sold it to them. In the early 1990s, a vocal contingent of astrophysicists and cosmologists contended that Gravity Probe B was way too expensive to be continued. They argued that the probe was effectively a physics project, but the money for it was coming from their astrophysical NASA budget. That budget, they pointed out, was shrinking with every passing year, and half a billion dollars constituted a disproportionate share for a project that would very likely only confirm something that everyone already believed. And even if Gravity Probe B were to find that the size of the frame-dragging effect differs significantly from the prediction of general relativity, no one except Everitt and his colleagues would believe it anyway. The investment in Gravity Probe B would immediately require that somebody spend another half billion dollars to build Gravity Probe C to confirm the discovery.

The NASA management responded to critics by putting together a review committee, which sided with Everitt. Although the committee included in its final report a "significant minority" who believed that the program was misguided, the majority of members felt otherwise. The project, they insisted, was "well worth its remaining cost to completion."



THE GYROSCOPES' HOUSING IS MADE OF FUSED QUARTZ, LIKE THE ROTORS THEMSELVES.

Now the probe is slated for launch by October 2000, and Dan Goldin, head of NASA, has publicly stated that he's behind Gravity Probe B all the way. That should be reassuring, considering how long it's taken the project to get off the ground. There was a time around 1964, after NASA first began funding it, when William Fairbank, a notorious optimist, was hoping to see it in orbit by the early 1970s. Fairbank died in 1989, and it was only last October, seven years later still, that the Stanford researchers got hold of their first major piece of flight equipment, the dewar, to start putting the actual satellite together. Now one of the wonders of the project is why the scientists involved have stayed with it. "If we had been talking 30 years when we first became associated with the project," says Daniel DeBra, "it would have been very hard to do. But none of us was that pessimistic. And there was never a time that the work was routine. We were pushing the envelope on virtually all the technology."

If that isn't enough, the experiment does have the kind of intrinsic interest that can keep a scientist motivated for quite some time. "This experiment is going to contribute to the deep fundamental knowledge of physics," says Lange, "the kind of knowledge that is related to questions that everybody asks until they get ruined by becoming an adult and don't ask questions anymore." D