The Gravity Probe B Bailout

By **Paul S. Wesson** and **Mark Anderson**

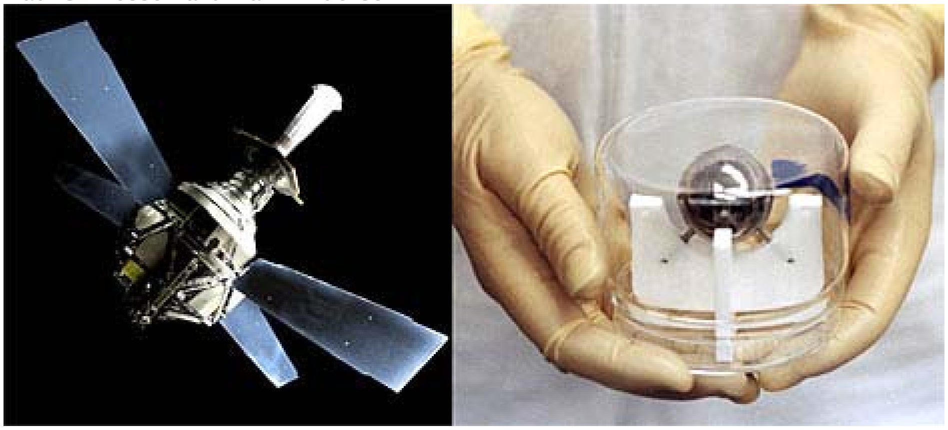

PHOTO: LEFT: KATHERINE STEPHENSON/STANFORD UNIVERSITY/LOCKHEED MARTIN; RIGHT: STANFORD UNIVERSITY/GRAVITY PROBE B

In 1964, before the term "black hole" was even coined, NASA began funding a project that would test the outer limits of the theory behind black holes, Einstein's general theory of relativity. Last May, with the project, called Gravity Probe B (GP-B), looking like a US $650-million flop, a NASA review board recommended that all funding be cut off by the end of September.

Now, in a dramatic turnaround, the Gravity Probe B team has secured non-NASA funding to press forward with data analysis of an experiment that has been bogged down by unexpected sources of noise. With the latest round of stopgap funds in place, the group holds out hope that it will either be able to verify or refute one of the most extreme predictions of Einstein's general theory of relativity.

GP-B is an orbiting set of precision gyroscopes measuring 6.4 meters long that was launched into low Earth orbit in April 2004. For nearly a year it studied the mild warping effect that Earth's gravitational field has on the fabric of space. It has already confirmed one prediction of Einsteinian gravity to a 1 percent confidence level—that the fabric of space compresses inside a gravitational field such that circles actually measure slightly less than 360 degrees.

However, a more subtle effect, involving the tug of Earth's rotation on space itself, has not yet been seen unequivocally. Because of an error in the gyroscopes' manufacture, GP-B's measurements have been riddled with wobbles that have made the ongoing data analysis for this "frame dragging" effect tremendously challenging. GP-B's final results were expected this year, but the GP-B team, based at Stanford University, appealed to NASA to continue funding through March 2010 to extract the precision measurements that team managers say still lie buried beneath a layer of noise.

With confidence in the project failing, NASA's funding slowed to a trickle this year, dropping to $500 000—not quite enough to keep the data analysis moving forward. So with some careful negotiations, the GP-B team secured matching $500 000 donations from Stanford and Richard Fairbank, CEO of Capital One Financial Corp. and son of the late physicist William Fairbank, an early proponent of this often controversial experiment. Nevertheless, the clock on the $1.5 million stopgap ran out on 30 September.

As this story went to press, GP-B project head Francis Everitt notified *IEEE Spectrum* that "a significant non-NASA agency" had committed $2.7 million to continue Gravity Probe B. This, Everitt hopes, will enable his group next year to reach a conclusion on a par with its original goal of testing the two Einsteinian effects down to the 1 percent confidence level.

The project was on very shaky ground, because even after years of data massaging, GP-B had weakly confirmed one of the effects, frame dragging, to only the 25 to 33 percent range. But as Everitt and GP-B spokesman Bob Kahn, of Stanford, told *IEEE Spectrum* via e-mail, a recent breakthrough in the modeling of behavior of the satellite's instruments has increased the data's accuracy “by a factor of 5 to 10”. The new results are to be presented early this month at an International Space Science Institute workshop on the nature of gravity.

NASA’s science advisory committee for the project has called the recent effort “heroic.” With this summer’s work, says the report, the GP-B team “has brought the experiment from what seemed like a state of potential failure, to a position where the [committee] now believes that they will obtain a credible test of relativity, even if the accuracy does not meet the original goal. In the opinion of the SAC Chair [Washington University physics professor Clifford Will], this rescue warrants comparison with the mission to correct the flawed optics of the Hubble Space Telescope, only here at a minuscule fraction of the cost.”

Arguably the most sophisticated spacecraft ever flown, GP-B contains some of the most precisely machined objects in the history of humankind. Those objects were harnessed to test effects that Einstein and his acolytes predicted some 90 years ago.

Central to GP-B’s operations is a redundant set of four superconducting gyroscopes that each must point in precisely the same unwavering direction in space throughout the satellite’s orbit. For the experiment to work, these gyroscopes must drift no more than 0.00000000001 (a one hundred-billionth) degree per hour. Even advanced navigational gyroscopes in airplanes or guided missiles lack this precision by a factor of at least 1 million. GP-B’s required accuracy, three orders of magnitude better than the finest gyroscope technology before it, would be good enough to shine a laser from Earth to the moon’s surface and keep that laser light within a bull’s-eye just one-tenth of a millimeter across.

GP-B was a difficult experiment to build and, at $650 million, was also quite expensive. For these reasons, its development became the subject of acrimonious debate in the scientific community: Many physicists wanted it, while many astronomers thought it unnecessary. Like other California-based matters, it came to represent a focal point of discontent between those in the San Francisco area and those in the Los Angeles area. Many Stanford people, in the north, wanted it built, while some Caltech people, in the south, wanted it scrubbed. (An exception in the latter camp was the Caltech black-hole expert Kip Thorne, who consistently supported the mission and was present at GP-B’s launch.)

PHOTO: R. UNDERWOOD/LOCKHEED MARTIN

GP-B ultimately stirred such controversy because the spacecraft's designers needed unprecedented precision to observe the effects relativity predicts—that gyroscopes inside a satellite orbiting Earth would experience two slight distortions because of Earth's gravitational influence. The first involves Earth's gravity warping the geometry of space and time ever so slightly, such that even a perfect gyroscope completing one whole orbit of Earth winds up with its axis a tiny bit off from the direction in which it originally pointed. This relativistic "geodetic effect" causes an Earth-orbiting gyroscope to drift 0.0000002 degree per hour—a factor of 20 000 above the expected sensitivity of the GP-B gyroscopes.

More subtle still is the frame-dragging phenomenon, in which Earth's spin pulls a small bit of space and time with it. Picture a bowling ball immersed in a pot of olive oil. Spin the bowling ball around and a small amount of the oil gets dragged around with the ball. Einstein said that the fabric of space and time itself gets tugged and twisted in a similar way by any massive rotating body. General relativity, in an effect first calculated 90 years ago by Austrian physicists Joseph Lense and Hans Thirring, predicts that an Earth-orbiting gyroscope would drift by an additional 0.000000001 degree per hour—100 times GP-B's projected gyroscope sensitivity.

These are minute effects that required cutting-edge solid-state physics, materials science, and electrical engineering to be able to measure. When Professor Leonard Schiff of Stanford and, independently, George Pugh of the U.S. Department of Defense first proposed the experiment that became GP-B in the early 1960s, some engineers at the time thought the technical and technological obstacles were insurmountable.

But other than the pure engineering challenges the project poses, scientists care about such relativistic details because there are many other places in the universe where geodetic effects and frame dragging, if they indeed do exist, would be practically impossible to miss. The geodetic effect is an extension of known and observed properties of gravity and space-time, such as light's tendency to bend in the presence of massive objects like the sun. (An entire subfield of astronomy, gravitational lensing, examines how light from distant quasars bends in the presence of intervening galaxies.) If the geodetic effect could not be observed in more astronomically mundane places like Earth's orbit, then something in the theory of general relativity would need serious reconsideration. No observation of the geodetic effect in some astronomically distant object—carrying its own galaxy of unknown intervening factors that might muddy the waters—could ever approach the certainty that a specially designed experiment like GP-B could provide.

And frame dragging in particular carries with it science fiction–like implications—including "time machine" space-times, in which a traveler flies out of a close encounter with a rapidly spinning black hole *before* she flies in. (Such cause-and-effect-violating scenarios are, not surprisingly, a subject of some contention among physicists, most of whom dismiss the black hole/time-travel possibility as mere mathematical legerdemain.)

Rigorously testing some of relativity's most far-flung predictions—in a controlled, orbiting laboratory environment—is the best opportunity science provides for testing the ground rules of some of the most extreme environments in the universe. Observing supermassive black holes and quasars from afar presumes we know the physics they follow. Even a minor alteration to general relativity—which anomalous GP-B results could suggest—would result in massive changes in the rules of the game when examining echoes of the early universe or shock waves emanating from a black hole.

The trick to witnessing both geodetic and frame-dragging phenomena has been ensuring that nothing but the shape of space-time disturbs GP-B's gyroscopes, so that the softest whisper of these relativistic signals may be observed from within Earth's comparatively weak gravitational field.

Regular mechanical gyroscopes are built around a spinning wheel that, by virtue of its rotation, resists any attempt to reorient its axis of spin. This principle, called conservation of angular momentum, explains why you don't fall over when your bike is moving but you do when it's standing still. Surrounding the gyroscope rotor is a frame and two gimbals that allow the machinery surrounding the gyro to rotate in any direction, while the rotor continues to point in its original direction. Mechanical gyroscopes are far from perfect, though, because friction between the rotor and the surrounding machinery causes torques that tweak the direction in which the rotor points, leading the gyroscope to drift. A good mechanical gyro will drift 0.05 degree per hour. The sensitivity of GP-B's measurements requires much better.

GP-B's gyroscope is a sphere made of fused quartz and silicon about the size of a Ping-Pong ball, machined to remarkable smoothness. The surface of the ball departs from that of a perfect sphere by no more than 40 atoms in thickness, making these four rotors the closest to an ideal sphere ever made. Any thicker than 40 atoms and the sphere's wobble would begin to drown out the relativistic signal scientists want to observe. By way of perspective, if GP-B gyroscope rotors were made the same size as Earth, their highest peaks and lowest valleys would represent deviations of no more than 2 meters.

These four superspherical rotors are ensconced in cavities in a block of fused quartz. Each gyroscope ball floats in a vacuum inside its cavity. After GP-B reached its final orbit in July 2004, it turned on a tiny jet of helium that blew on the gyroscope spheres, making them spin as if they were beach balls in a pool being sprayed by a garden hose. Once the gyros had spun up (and the helium gas had been expelled from the gyroscope chambers), electronics inside each gyro monitored its spinning ball down to nanometer-scale precision such that any slight movement toward the chamber walls could be compensated for by GP-B firing its thrusters. Like a sideshow entertainer spinning plates on broom handles, the four spinning objects in GP-B were the central focus of the whole experiment. The satellite moved itself at the slightest hint of a displacement in the gyroscope rotors.

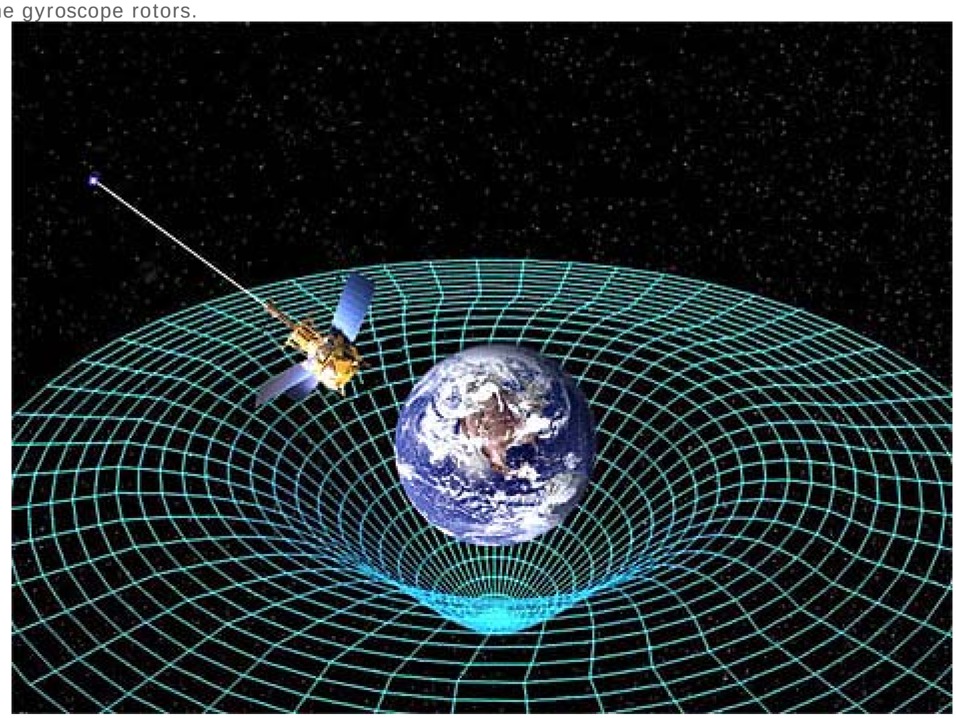

PHOTO: NASA

One potential disturbance that must be kept away from the gyros is Earth's magnetic field. GP-B screened out external magnetic influence by encasing the gyros in a coffin-size chamber made of 1.25-centimeter-thick lead. Because it's very malleable, the lead shielding is called GP-B's "lead bag," even in GP-B technical documents. During operation, the bag was cooled down to 1.7 degrees above absolute zero using more than 2 kiloliters of liquid helium. At these low temperatures, the lead becomes a superconductor, losing all electrical resistance and screening out magnetic fields to the point that the gyros experienced no more than 3 microgauss—the sort of magnetic silence one finds in deep interstellar space.

The gyroscope rotors were coated with a thin layer of the metal niobium. At such low temperatures, niobium is also a superconductor. And spinning superconductors give off a slight magnetic field (called a London moment after the German physicist Fritz London, who discovered it) that is precisely aligned with the superconductor's spin axis. Superconducting electronics in the gyroscopes—devices called SQUIDs, which are extremely sensitive to slight variations in small magnetic fields—then kept track of any gyroscopic deviation. GP-B was launched into an orbit with an altitude of about 650 kilometers over the poles. Using an onboard telescope, GP-B kept its sights on a reference star called IM Pegasi to establish a fixed, distant reference point against which any variations in the gyroscopes' directions could be measured.

Of course, no matter how accurate the telescope, nothing on GP-B would have mattered if it hadn't had the most accurate gyroscope in the world. To create such a technological marvel, the GP-B team required at least six variables to be minimized to the edge of technological capability. All were in the service of keeping the gyroscopes' drift to within 0.00000000001 degree per hour:

- The gyroscope rotor itself couldn't depart from spherical perfection by any more than 10 nanometers.

- Via superconducting lead shielding, the magnetic field felt by GP-B's gyroscopes had to be kept to 3 microgauss or less.
- The composition of the gyroscope rotor had to be pure to one part in a million to ensure there were no unexpected density variations or electromagnetic properties.
- Although it is in free fall at a nominal zero *g*, GP-B is no different from any other satellite, occasionally experiencing the slightest acceleration from its surroundings. But in GP-B's case, those accelerations had to be compensated for by quick firings of the satellite's thrusters—making the gyros experience accelerations that were never more than one-hundred-billionth of 1 *g*.
- The gyro rotors had to be kept spinning in a practical vacuum, slightly less than the atmospheric pressure on the surface of the moon.
- Any residual electric charge on the gyroscope rotors had to be reduced to 0.02 nanocoulomb.

GP-B cleared each of these hurdles with room to spare, but after it was in orbit and returning data to Earth, mission scientists discovered that a seventh challenge had not been met. The gyroscope rotors had retained a small electric polarity in their niobium outer layer. Spinning hundreds of times per second, these electric polarizations manifested as tiny magnetic fields on the rotors' surface. Although the GP-B team anticipated difficulties such as the previous six mentioned, this is the one that got out of control.

The problem, in retrospect, started years before launch, when GP-B engineers tested a mock-up of their rotor with patinas of niobium just like the ones the actual GP-B gyroscope rotors would eventually be coated with. However, Everitt recalls, the electric probe used to test the tiny fields emitted by the coatings worked only on flat surfaces. So the engineers settled for a mock-up "rotor" that was actually a flat surface coated with niobium.

"It all looked great, and it all fitted with the [theoretical] model," Everitt says. "And so, wrongly, we relaxed."

After GP-B was in orbit, and the data began to look odd, Everitt and his collaborators revisited every potential source of error and ultimately realized that their mock-up rotor had given them a false sense of security. The niobium coating was the problem.

To understand the consequences, you must first realize that the rotors were never meant to hold a fixed-spin axis. Instead, they were always expected to exhibit predictable "polhode" behavior—a phenomenon well known since the 18th century in which freely spinning objects slowly tumble through a predictable series of wobbles. A rotor's spin axis, under no other influence but classical physics, traces out a series of ever-widening ellipses. So in a perfect world the actual technical mission of GP-B was to follow the rotors' polhode motion carefully and find any deviations that could not be explained by classical physics.

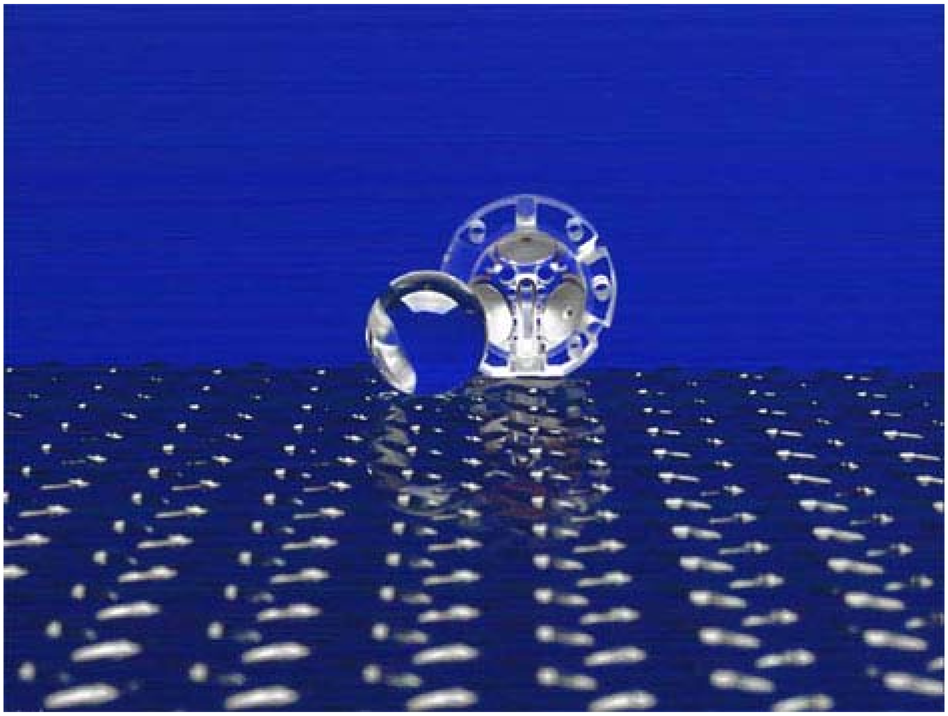

PHOTO: STANFORD UNIVERSITY/GRAVITY PROBE B

GP-B scientists soon found, however, that the rotors were not just tracing a well-known Newtonian pattern with tiny sidesteps predicted by Einstein. Rather, those spinning rotors were also heeding a third influence: electromagnetism. The final patch of niobium sprayed onto the rotors had effectively polarized the sphere and left a tiny surplus charge that, when spun up and translated into magnetic fields, added a new layer of wobble to account for. GP-B collected data for 353 days in 2004 and 2005 and then spent an additional 46 days conducting tests on the gyros to deduce precisely where those additional tiny magnetic fields lay.

Fortunately, GP-B's extra wobble can be computationally simulated and thus subtracted from the signal. But it requires painstaking number crunching to derive the magnetic influence on each gyro at each moment in its 353 days of observation. The results so far have been a confirmation of the geodetic effect as predicted by relativity, with the confidence level the team had hoped for: 1 percent.

Frame dragging, a weaker effect, has been more difficult to extract from the data. Confirming, amending, or disproving this most peculiar prediction of relativity requires a more exacting reduction of the niobium-coating noise. Everitt says that the work his team did through September—and will continue into 2009—involves squeezing one clever twist from the data that they hope will enable them to extract the minuscule frame-dragging signal.

The potential solution arises from an observation from the 18th century. In 1729, a British astronomer named James Bradley discovered that the apparent position of stars in the sky, as seen through a telescope, varied by tiny amounts throughout the course of a year. He discovered something called stellar aberration, a small tweaking of a star's position produced by the fact that any telescope is moving through space as Earth moves around the sun. And with the star's light moving at the speed of light, it actually takes about a nanosecond for the light to move from the outer lens of the telescope into the eyepiece or, in the case of GP-B's telescope observing its reference point IM Pegasi, onto the light-sensitive chip that records the star's light. During that nanosecond, the telescope will have moved a tiny bit. The direction and amount by which the telescope moves during that nanosecond varies depending on the time of year. So there's a natural wobble—an aberration, in the technical parlance—of any star's position throughout the course of the year. On top of the yearly aberration, the orbiting GP-B telescope experienced an additional aberration as the satellite traced out its motion around Earth.

GP-B chief scientist George "Mac" Keiser realized that the slight orbital and annual aberration of IM Pegasi's image—when compared with the direction in which the gyroscopes were pointing—would produce a further perceived wobble in the data. But this virtual wobble was a known, well-understood phenomenon and could be simply calculated. And since each of the four gyroscopes was experiencing different electromagnetic effects from its outer niobium coating, the aberration could in fact serve as a “reference wobble” that would enable GP-B number crunchers to sort out how each gyroscope was being torqued by the niobium coating.

Subtract the niobium effect, Everitt says, and GP-B’s signal should be much closer to the ideal single-digit percentage error bars that his team has been shooting for.

So GP-B’s verdict on frame dragging, one of relativity’s most astonishing predictions, may yet emerge from the 2 terabytes of raw data now shared by the Stanford GP-B analysis team’s 20 Sun Microsystems workstations.

“This is what Bill Fairbank used to call the ‘anti-Murphy Law,’” said Everitt. “When you finally understand what you’re doing, nature comes to help.”

Acknowledgements

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About the Authors

Paul S. Wesson is a Cambridge-educated cosmologist who has published more than 240 articles and 9 books. He worked on the Gravity Probe B experiment from 1990 until its 2004 launch. His latest book is *Brave New Universe*, coauthored with Paul Halpern (Joseph Henry Press, 2006). He has written popular-science articles for *Analog, New Scientist*, and *Sky & Telescope*.

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