raster scan. That is to say, each pixel in the scan has a great deal of overlap with its neighbors. Each image scan is followed by a similar scan of the reference point-source star. The reconstruction algorithm is an iterative deconvolution calculation that uses the observed smearing of the known point source to extract the true image from its presumably identical smearing. A free parameter (effectively a Lagrange multiplier) is varied until the recovery of additional information from the image is maximized and any further recovered "information" begins to look unrealistic.

The sensitivity of this technique for faint sources lets the group exploit polarization information to strengthen the scattering-disk hypothesis. If the extended HL Tau source is indeed a disk of scattering dust particles, starlight scattered from its outer edges will be polarized perpendicular to the disk plane. Interposing a polarizer oriented in this direction, the group did indeed see the full, asymmetrically extended HL Tau image; but with the polarizer axis parallel to the apparent disk plane the image was no longer resolvably extended.

Lynds 1551/IRS5 is a very faint infrared stellar source in the same Taurus molecular cloud complex in which HL Tau was born. Presumably because it is even younger than HL Tau, Lynds 1551/IRS5 has not yet extricated itself from the cloud sufficiently to be seen at visible wavelengths. The suspicion that IRS5 might have a circumstellar disk was raised by the fact that one sees a pair of very energetic jets bursting forth from the cloud, presumably resulting from highly collimated material ejected by the star. A circumstellar disk would serve as a mechanism for such a polar collimation of ejecta. The group has indeed now found evidence for an infrared scattering disk, about 500 AU wide, around this faint star, still imbedded in its womb. —BMS

Reference

1. H. Aumann, F. Gillet, C. Beichman, T. de Jong, J. Houck, F. Low, G. Neugebauer, R. Walker, P. Wesselius, Ap. J. (*Letters*) **218**, L23 (1984).

Orbiting gyro test of general relativity

Over twenty years have elapsed since Leonard Schiff at Stanford and, independently, George E. Pugh at the Defense Department predicted[1] that a gyroscope in orbit about Earth would precess as a consequence of Einstein's general theory of relativity. Such behavior depends on an aspect of the theory of gravity that remains untested to this day. Although the concept is simple, the experiment is formidable: The precession is about 44 milliarcsec/year, to be measured with an accuracy of 1 milliarc-sec per year. Undaunted, Schiff, together with Stanford colleagues William Fairbank and Robert Cannon, respectively, set up a program to develop the experiment. Since 1962, a Stanford team led by Francis Everitt and later having the support of NASA's Marshall Space Flight Center, has patiently and persistently toppled[2] many technical barriers, bringing the experiment from the realm of the improbable into the world of the possible. In late 1980, a committee of 16 scientists and engineers convened by NASA spent five days reviewing the technical readiness of the experiment, which is called the Gravity Probe B. They gave it a sound endorsement and concluded it was now ready to proceed to its flight phase.

Since then the Stanford team has endeavored to develop a satisfactory flight program. Eighteen months ago, NASA rejected as too expensive a $200- to $300-million plan that would have involved an elaborate, land-based engineering development followed by the launch in 1992 of a very large (2400-kg) spacecraft. During the past year, the design has been greatly simplified. The proposal reduces the spacecraft weight to 1300 kg and sets forth a less costly plan to develop the high-technology portion of the experiment (the instrument assembly). The system would be tested aboard the Space Shuttle in three to four years, with this first phase costing $50 million. The experiment would then proceed with a subsequent free flight in space if all systems worked during the shuttle flight.

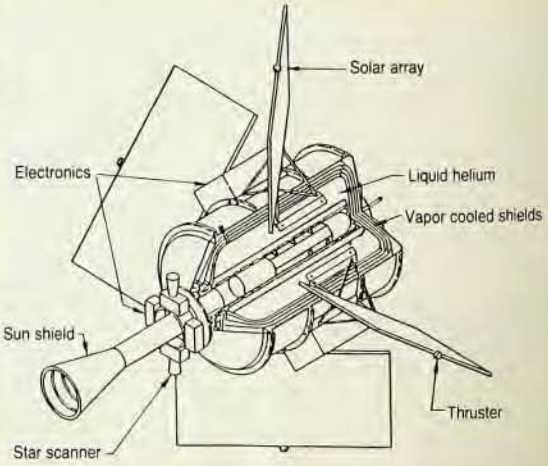
Last fall, NASA unexplainedly deleted funds for the Gravity Probe B from its FY 85 budget request. Several prominent physicists wrote to NASA in support of the experiment, and the Space Science Board responded directly to NASA's budget cut with a strong endorsement of the Gravity Probe B, stating that it "fully addresses [their] highest priority science objective in gravitational physics." Frank McDonald, chief scientist for NASA, told us that although NASA had not yet made a final decision on Gravity Probe B, NASA is optimistic about the prospect that it will go ahead with an engineering test on the Shuttle.

During the years of development of the Gravity Probe B, theoretical interest in the project has, if anything, intensified. Because the gyroscope can detect spin-sensitive aspects of the gravitational interaction to which other (easier) tests of relativity are insensitive, it may provide a qualitatively different test of Einstein's theory of general relativity—and a negative result is not necessarily unexpected. In his letter of endorsement to NASA, Chen Ning Yang (State University of New York, Stony Brook) felt he spoke for many theorists in asserting that Einstein's general theory of relativity, while profoundly beautiful, may need to be amended. One reflection of the inadequacy of the theory in its present form is the lack of success in attempts to quantize it. Yang believes that the correct, geometrically symmetric form of the theory will most likely involve spin and rotation.

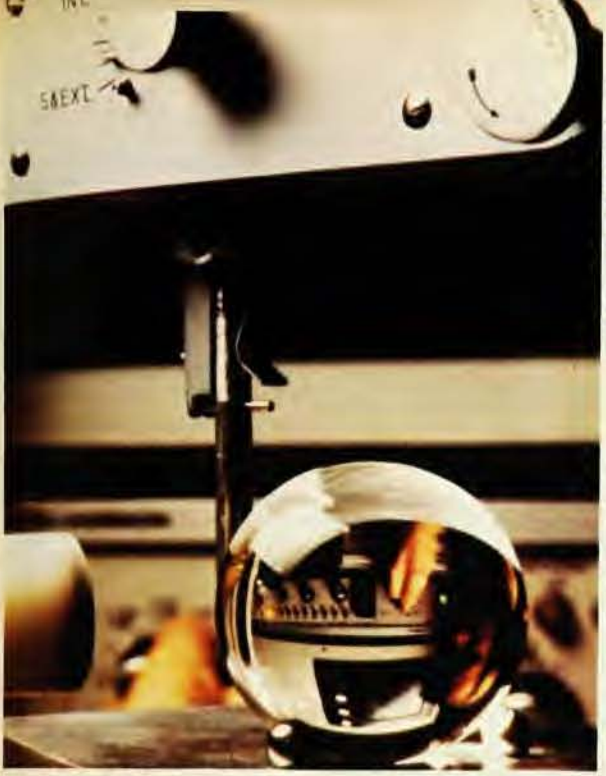
Gyroscope precession. Schiff deduced that two effects would cause the precession of the gyroscope, corresponding to two terms in the following equation:

$$\mathbf{\Omega} = \frac{3GM}{2c^2R^3}(\mathbf{R}\times\mathbf{v}) + \frac{GI}{c^2R^3}\left[\frac{3\mathbf{R}}{R^2}(\boldsymbol{\omega}\cdot\mathbf{R}) - \boldsymbol{\omega}\right]$$

where $\mathbf{\Omega}$ is the precession rate, $\mathbf{R}$ and $\mathbf{v}$



Gravity Probe B would contain four gyroscopes mounted along the main axis of the satellite and contained within the helium dewar. Gas escaping from the dewar would drive the proportional thrusters to keep the satellite axis pointed towards a distant star. This free-flight version is the final step after the proposed test aboard the Space Shuttle.



Quartz gyroscope being measured to determine any deviations of its surface from perfect sphericity. Imperfections could create torques that could mask the precession to be observed. (Photo by Michael Freeman.)

are the position vector and velocity of the gyroscope, and M, I and ω are the mass, moment of inertia and angular velocity of Earth. The first term, called the "geodetic precession," results from the motion of the gyroscope through the warped space–time of the gravitational field. The second, termed the "motional precession," stems from the "dragging" of the inertial frame by the rotation of the Earth. The former bears some relation to effects seen in other tests of gravitation, but the second term is entirely novel.

By analogy with electromagnetic fields, the geodetic and motional precession terms can be related to spin–orbit and spin–spin couplings, respectively. The analogy to electromagnetism is valid in regimes where space–time is nearly stationary, as it is around the Earth or around a quiescent black hole. In these cases, this space–time metric can be written in a form in which two potentials exist in curved three-space—a scalar "gravitoelectric" and a vector "gravitomagnetic" potential. The framework allows one to derive the gravitational equivalent of Maxwell's equations.

Gravitomagnetic fields are crucial not only to the intrinsic structure of the gravitational theory but also to particular applications of it. Several current explanations of such astrophysical phenomena as the relativistic jets emanating from double-lobe radio sources relate this behavior to the gravitomagnetic fields around massive rotating black holes.

In this framework, Earth is surrounded by lines of the gravitoelectric field directed radially inward and by dipolar lines of the gravitomagnetic field appropriate to a rotating, uniformly "charged" sphere. The gyroscope is the analog of a magnet, with its gravitomagnetic dipole moment being simply its spin angular momentum. The second term in Schiff's equation results from the torque of the Earth's gravitomagnetic field on the gyroscope, and is thus of the greater interest to theorists. (In his 1972 Stanford thesis, Daniel Wilkins applied this analogy to the gyroscope experiment, and Julian Schwinger independently published[3] a paper on this and other applications of the analogy. Kip Thorne has elaborated[4] upon the approach.)

As luck would have it, the term of greater theoretical interest is by far the more difficult to determine experimentally. The geodetic precession is estimated to be about 6.9 arcsec/year while the motional precession should be only 0.044 arcsec/year when the gyroscope is in polar orbit at an altitude of about 300 miles. Thus the criterion for detectability for the orbiting gyroscope was set at 1 milliarcsec/year.

The basic design of the experiment is to orbit a liquid-helium dewar containing four rotating quartz spheres coated with niobium and cooled to superconducting temperatures. The rotors will be suspended electrically, and because the gyroscopes will be in free fall along with their supports, the perturbing torques created by the support will be very small. To reduce the accelerations on the gyroscopes as much as possible, the satellite will be equipped with a "drag-free" control system of a design developed at Stanford and already proven in space. The alignment of the spin vectors of the homogeneous spheres will be detected by a SQUID magnetometer that responds to changes in the orientation of the London magnetic moments of the gyroscopes. The direction of these spins will be referenced to a distant star, Rigel. A telescope and associated controls will keep the axis of the satellite pointing towards of this guide star. The gyroscope spin axes will initially be parallel to this direction.

Gravity Probe B components. Each element of the overall system is a research project in its own right. The gyroscope itself is an adaptation of a design originated by the late Arnold Nordsieck (University of Illinois) and developed by Honeywell. The Stanford version will operate at cryogenic temperatures, require tighter manufacturing tolerances and have a different method of spin-up to accelerate the sphere to the desired angular velocity (170 Hz is optimum). So far, a ground-based version of the gyroscope (directed by John Lipa) has operated in the laboratory at Stanford for over 12 000 hours at low temperature. The laboratory suspension system (built by the late John Nikirk) supplies 20-kHz support voltages to three mutually perpendicular sets of saucer-shaped electrodes. The spin-up system must sufficiently reduce the drag torque and avoid heating the sphere above its superconducting transition temperature. The spheres will be set rotating by a gas jet flowing in a circumferential channel, according to a design by Dan Bracken (now a private consultant). At a temperature of 1.8 K and pressure of 10^{-10} torr, the rotors should have an exponential decay time of 4000 years. The required low vacuum will be obtained by a bake-out procedure (developed by John Turneaure) that has been tested—but not after using an air jet to spin the rotor. While development has proceeded, the experimenters have anlayzed the action of rotation on any deviation of the balls from perfect sphericity to ensure that any perturbations were sufficiently small. To do this analysis, George Keiser extended work by Gary Matchett (Honeywell) and Peter Eby (NASA Marshall).

The London magnetic moment of the superconducting rotor is nearly perfectly aligned with the angular velocity vector. (Any deviations of the two vectors due to inhomogeneities may cause a modulation of the precession signal but should not affect the average direction, the Stanford analyses indicate.) As the London moment rotates, it will generate a cancelling current in the two loops coupled to a SQUID magnetometer. (Contributors to the gyroscope readout include John T. Anderson, now at Hewlett–Packard, Robert Clappier, Jim Lockhart and Blas Cabrera, both of Stanford, and Palmer Peters, NASA Marshall.)

A major concern is that the overall measurement of the gyroscope precession will be affected by null drifts or by low-frequency noise in the gyro or telescope readouts. The Stanford team proposes to minimize these effects by rolling the spacecraft at a period of about 10 minutes about the line of sight to the star. The normals of the planes of the two magnetometer pick-up loops are perpendicular to this rotation axis, so the loops rotate with the spacecraft. As the readout loops rotate, the angle of the London moment—and hence the flux through the loops—varies periodically. The relativity signal thus becomes sinusoidal, with the amplitude indicating its magnitude, and any long-term drifts in the null signal just causing an upward or downward displacement of the curve.

Furthermore, without roll, the precession angle would be a linearly increasing signal, which would have to be integrated over a very long time period. However, the noise becomes a problem after an integration time longer than the reciprocal of the frequency below which the detector noise power increases, because the precession angle looks like a low-frequency signal. With the roll, the gyroscope precession appears not as a dc signal but as an ac signal at the roll rate. The signal integration is effectively chopped at times equal to the period of the roll, and the $1/f$ noise is not a problem.

For precision magnetic readout, extraneous magnetic fields must be considerably below the London value of 1.2×10^{-4} gauss. The large regions of ultralow fields will be obtained by a novel technique in which a superconducting shield is folded into a small cross section and cooled below its transition temperature. As the shield is then expanded, the field decreases to keep the total flux constant. The Stanford group has so far used a variant of this method to reduce fields to as low as 2×10^{-8} G for as long as 18 months. Cabrera developed the method, following a suggestion by William Hamilton (Louisiana State University).

The fused quartz ball and its niobium coating must be especially round and homogeneous. The material from which the rotor is made cannot have density variations greater than 3 parts in 10^7. The density variations will be determined to this accuracy by measuring fluctuations in the index of refraction (following a method devised by John Bates and Michael Player of the University of Aberdeen, Scotland). After placing the sample cube on a movable carriage in a cell with an index-matched fluid, they shine a laser light through the cell and move the cube from side to side. A laser interferometer reads the optical path length, from which the density is derived. A precision lapping machine (developed by Wilhelm Angele of NASA Marshall) will turn these quartz cubes into balls of the required roundness. The 39-mm-diameter balls must not deviate from perfect sphericity by more than 10 nm. Using a roundness-measuring instrument, Lipa and Graham Siddall (now at Hewlett–Packard) have developed a method to generate, by computer, contour maps of the rotor surface, accurate to about 2.5 nm. The niobium layer deposited on the quartz sphere must be both robust and uniform.

The four gyroscopes in their housings, and the reference telescope are held together in a quartz block structure by molecular adhesion; this requires the surfaces to be flat within 1/20 of a wavelength. This optical contacting avoids mechanical creep and eliminates differential thermal contraction. The entire structure is enclosed in a dewar with a capacity of 1245 liters of liquid helium at 1.8 K. This vessel is very similar in design to the dewar being developed by Ball Aerospace for the Cosmic Background Explorer (COBE). The dewar should hold the helium for 14 months, although Everitt feels that 8 to 10 months of operation should still yield useful information. It will contain the porous plug control invented at Stanford by Peter M. Selzer (Ford Aerospace), Fairbank and Everitt. This plug regulates the rate at which helium boils off by balancing the pressure drop across the plug with an opposing pressure caused by the fountain effect in superfluid helium.

The escaping helium gas exits through proportional thrusters with its flow controlled by three servosystems. One servo points the telescope within 50 milliarc-sec of the guide star, the second controls the satellite roll and the third adjusts for any accelerations. (The thrusters were developed at Stanford by Daniel DeBra, John Bull, Jeng-Heng Chen and Russell Hacker.) For drag-free operation, sensors monitor the relative position of a spherical proof mass placed in a shielded evacuated cavity near the center of mass of the spacecraft. This mass is traveling in a nearly ideal orbit. The thrusters maneuver the craft essentially to follow it. This drag-free system improves the averaging of the residual accelerations on the gyroscopes. Pugh first suggested the concept of a drag-free satellite in his original suggestion of the experiment, and Benjamin O. Lange at Stanford developed the idea.

The telescope for the orbiting gyroscope consists of a folded Schmidt–Cassegrain system with a focal length of 381 cm and an aperture of 14.2 cm. The Stanford lab has an artificial star on which to test the telescope. (Both were built by Donald E. Davidson of Optical Instrument Design Co.) The data-processing system, among other tasks, subtracts the gyro and telescope signals, whose scale factors must be nearly matched, and derives signals used in the satellite's attitude control. (Richard A. Van Patten built the system and has contributed to other electrical systems.) The processing of the signals in the data chain could give rise to error propagation, so the Stanford group is performing an end-to-end error analysis to verify that the sum of errors from each of the subsystems does not exceed the design maximum. (This work has been the job of John Breakwell, Thierry Duhanel and Richard Vassar, all now at TRW.) They also plan to check for systematic errors after taking data by varying the experimental parameters.

Flight plans. With most of the subsystems in a tractable state, Everitt envisons now a shift to systems engineering, as the groups assemble the pieces into a workable whole. If they receive funding for a shuttle test in three years, they would send up a dewar for the flight period of seven days. The shuttle has a relatively high-g environment (10^{-5} g). The test would verify overall operation and gather preliminary data on the gyro precession rate. Part of the flight proposal calls for the shuttle to roll with a 10-minute period to simulate the effects of the satellite roll. The telescope would be mounted inside the dewar but would not be functional.

If the test is successful, the Stanford group would refurbish the dewar and instrument and fit them into a satellite to be launched by the shuttle in another two years or so. Everitt would ideally like a 14-month flight, allowing for a month to set up and a final month of in-flight calibration, bracketing the year of data collection. —BGL

References

1. L. I. Schiff, Proc. Nat. Acad. Sci. **46**, 871 (1960); Phys. Rev. Lett. **4**, 215 (1960); G. E. Pugh, "Proposal for a Satellite Test of The Coriolis Prediction of General Relativity," WSEG Research Memorandum No. 11, Weapons System Evaluation Group, Department of Defense.
2. J. T. Anderson, B. Cabrera, C. W. F. Everitt, B. C. Leslie, J. A. Lipe, in *Proc. of the Second Marcel Grossman Meeting on General Relativity*, R. Ruffini (ed.), North-Holland, New York (1982).
3. J. Schwinger, Amer. J. Phys. **42**, 507 (1974).
4. K. S. Thorne, in *Near Zero: New Frontiers in Physics*, C. W. F. Everitt, B. S. Deaver, P. Michelson, eds., W. H. Freeman, San Francisco (to be published, 1984). □