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Review of
Gravity Probe B

Task Group on Gravity Probe B
Space Studies Board
Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL ACADEMY PRESS
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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Cover: Gravity Probe B gyroscope rotor assembly.

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Review of Gravity Probe B

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Preface

In response to a request by the NASA Administrator, the National Research Council (NRC) has conducted an accelerated scientific review of NASA's Gravity Probe B (GP-B) mission. The review was carried out by the Task Group on Gravity Probe B, under the auspices of the NRC's Space Studies Board and Board on Physics and Astronomy. The specific charge to the task group was to review the GP-B mission with respect to the following terms of reference:

1. Scientific importance—including a current assessment of the value of the project in the context of recent progress in gravitational physics and relevant technology.

2. Technical feasibility—the technical approach will be evaluated for likelihood of success, both in terms of achievement of flight mission objectives but also in terms of scientific conclusiveness of the various possible outcomes for the measurements to be made.

3. Competitive value—if possible, GP-B science will be assessed qualitatively against the objectives and accomplishments of one or more fundamental physics projects of similar cost (e.g., the Cosmic Background Explorer, COBE).

The task group was assembled by December 1994. It included experimental physicists with considerable experience in the conception, design, and successful execution of complicated experiments, engineers who have played pivotal roles in the space program, and theoretical physicists whose specialty has been gravitational theory, as well as a distinguished theorist from outside this particular subfield.

During the course of the study the task group met three times. The first meeting, held at Stanford, California, on January 10-12, 1995, was an extensive on-site review of the relativity mission, including tours of both the Stanford and Lockheed GP-B facilities. During this review the Stanford team addressed the scientific importance of GP-B, discussed the resolved and unresolved scientific and technological challenges, and described various spin-offs of the 30-year-old project. The second and third meetings were held on February 10-11 and March 3-4, 1995, in Washington, D.C. At these meetings some invited guests presented alternative views on GP-B as well as other NASA missions such as the Stratospheric Observatory for Infrared Astronomy (SOFIA) and the Space Infrared Telescope Facility (SIRTF).

As part of the assessment process the task group solicited input from the astrophysics and general relativity communities. Solicitation letters were sent to approximately 15 leaders in the field requesting their input on the issues raised in the charge. In addition, general solicitation notices were placed in the newsletters of the American Astronomical Society and the Astrophysics Division of the American Physical Society. A notice to the worldwide general relativity community was placed on an Internet bulletin board maintained at Queen Mary College in London. In its deliberations the task group considered the diversity of opinions expressed in responses to these public notices.

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Summary

BACKGROUND

The experiment now known as Gravity Probe B (GP-B) was conceived more than 30 years ago. Bold and daring in concept, it has been under continuous development ever since. The aim of the experiment is to measure, rather precisely, an effect that is predicted by all viable relativistic theories of gravity but has not yet been observed. Just as Newton's law of gravity is paralleled by Coulomb's law of electricity, so also it is expected that the force between currents of electrical charge, described by Ampere's law, should be paralleled by a force between "currents" of flowing matter. It is this force that has never been directly observed.

A useful perspective on the GP-B experiment can be obtained from a historical profile of its funding. Until the late 1980s, the project was funded at a level of $1 M to $2 M per year to develop and demonstrate the necessary technology. Funding was then increased to permit detailed engineering of the various subsystems and thorough ground testing. The funding level reached about $30 M/yr in FY 1992, when the project entered a "science mission" phase involving development of an appropriate spacecraft to carry the experiment. Since then the funding has been approximately $50 M/yr.

When the project was last reviewed for NASA 4 years ago, the Parker Committee, an ad hoc review committee convened by NASA Associate Administrator for Space Science and Applications Lennard A. Fisk and chaired by Eugene N. Parker of the University of Chicago, recommended that if GP-B were to go forward, it must be properly funded. That committee considered an appropriate funding level to be about $50 M/yr until the time of launch, which was anticipated to be late in the 1990s. Subsequent funding has in fact been at this level, and has allowed highly skilled teams to address thoroughly various technical details of the experiment and to start building the flight instrument package and integrating it into a spacecraft. By the end of FY 1995 about $240 M will have been spent on the project. NASA estimates that another $340 M will be needed for completion, including launch and subsequent data analysis.

SCIENTIFIC MOTIVATION

Like most other fields of science, Einstein's theory of gravity, the general theory of relativity or GR, has developed its own notation and jargon. Despite the simplicity and economy of its underlying assumptions, the theory in full glory leads to intensely complicated nonlinear equations. Indeed, the equations have been fully solved only in a few special instances. However, much of the mathematical complication can be removed by assuming that all gravitational fields are weak. The equations then reduce to a form remarkably similar to those governing electromagnetism. Terms appear that are analogous to the electric field caused by charges (the *gravitoelectric field*, produced by masses), and to the magnetic field produced by the flow of charge (the *gravito-magnetic field*, produced by the flow of matter). A spinning ball of electrical charge produces a well-prescribed static magnetic field, and correspondingly a spinning mass such as the Earth is expected to produce a static gravitomagnetic field. Of course, general relativity has important differences from electromagnetism, as well: in particular, it represents gravitational forces as arising from geometric curvature in the structure of space and time.

Gravity Probe B aspires to detect and measure, at the 1 percent level, the gravitomagnetic field produced by the spinning Earth through a spin-spin interaction with an orbiting

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gyroscope. This effect of the gravitomagnetic field is often referred to as "frame dragging," or the Lense-Thirring effect. In addition, GP-B will accurately measure the much larger "geodetic" precession, a combination of the effects of spin-orbit coupling and space-time curvature.

In the quarter century since inception of the GP-B project, many other tests of Einstein's theory of gravity have been made. The delay and deflection of light signals passing close to massive objects have been measured with increasing precision and found to agree with the predictions of GR at the 0.1 percent level. Geodetic precession has been detected and measured with 2 percent accuracy by laser ranging to the Moon. Gravitational radiation from accelerated masses in a binary pulsar system has been shown to be consistent with GR at the 0.4 percent level. Some of these tests involve gravitomagnetic effects related to the translational flow of matter, in combination with other relativistic gravitational effects, and therefore they provide indirect evidence for the existence of gravitomagnetism. By contrast, GP-B proposes to provide a direct test of gravitomagnetism caused by rotation, in isolation from other relativistic gravitational effects.

The past quarter century has also seen the development of exquisitely sensitive new instruments based on developing technologies and located both on Earth and in space. Some of them have provided the means to probe more and more deeply into the nature and evolutionary history of the universe. Observations with such instruments have yielded one surprise after another, and they raise perplexing questions about missing mass, the age of the universe, and the circumstances giving rise to the large-scale distribution of matter in space. In the past, laws of nature previously considered sacrosanct have sometimes been found deficient when subjected to much closer scrutiny or applied to new phenomena. As long as some discoveries defy understanding, it is important to continue testing nature's most fundamental laws.

CONCLUSIONS
Scientific Importance

The frame-dragging effect predicted by our principal theory of space and time, general relativity, has a deep conceptual significance involving the connections between rotation, distant matter, and absolute space. Frame dragging is a direct manifestation of gravitomagnetism. Its consequences have found important astrophysical applications in, for example, models of relativistic jets observed streaming from the cores of quasars and active galactic nuclei. A 1 percent measurement of the predicted frame-dragging effect would be a significant and unique test of GR. Gravity Probe B is one of the few space missions NASA has conducted with relevance to fundamental physics. If successful, it would assuredly join the ranks of the classical experiments of physics. By the same token, a confirmed result in disagreement with GR would be revolutionary.

Since GP-B was conceived, significant progress has been made through experimental studies of gravity, both in improved precision and in performing qualitatively new tests. These tests are so constraining that there are now no examples of alternative theories that are consistent with the experimental facts and predict a frame-dragging effect different from that predicted by GR at a level GP-B could detect. Yet the basic weakness of the gravitational force means that GR has been tested much less thoroughly than the other fundamental theories of physics. Nevertheless, along with most physicists this task group believes that a deviation from GR's prediction for frame dragging is highly unlikely.

In addition to detecting the new gravitomagnetic effect of frame dragging, Gravity Probe B should be able to measure the geodetic precession of its gyroscopes to an unprecedented accuracy of about 75 parts per million (ppm). This result would provide a factor-of-20 improvement in the measurement of space curvature per unit mass (now known to about 2 parts in 1000) and would tightly

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constrain the deviations from GR predicted by other theories of gravity in the weak-field limit.

Technical Feasibility

The task group is highly impressed with the extraordinary talents and abilities of the technical team assembled to create Gravity Probe B. The group has consistently solved technical problems with great inventiveness and ingenuity. Moreover, in the course of its design work on GP-B the team has made brilliant and original contributions to basic physics and technology. Its members were among the first to measure the London moment of a spinning superconductor, the first to exploit the superconducting bag method for excluding magnetic flux, and the first to use a "porous plug" for confining superfluid helium without pressure buildup. They invented and proved the concept of a drag-free satellite, and most recently some members of the group have pioneered differential use of the Global Positioning System (GPS) to create a highly reliable and precise aircraft landing system.

The task group finds progress in construction of the actual GP-B apparatus to be very impressive, as well. Working in concert with a team from the Lockheed Missiles and Space Company, the Stanford group is well on its way toward putting GP-B into space before the end of the decade, providing that the funding level is sustained. The task group has found no serious technical impediments to meeting the existing launch schedule. The spacecraft, experimental package, and projected methods of operation are well designed to meet the scientific requirements and prove the results valid. The team is well prepared to cope with a wide range of unanticipated phenomena. The task group considers the overall complexity of GP-B to be somewhat greater than that of the Cosmic Background Explorer (COBE) but much less than that of the Hubble Space Telescope (HST). An ordinary hardware failure is no more likely than in other comparable space missions. Furthermore, GP-B has been designed with extensive in-flight testing of all parts, four independent sensor gyros to provide immediate

confirmation of results, and in-flight calibration using observations of the aberration of light caused by the motion of the satellite.

Nevertheless, the extraordinary experimental requirements and the impossibility of ground tests of some critical systems at the necessary level of accuracy introduce significant risks. Despite an extensive list of detailed questions put to the GP-B team by the task group, no specific weakness or likely points of failure have been identified. A majority of the task group believes that GP-B has a reasonably high probability of achieving its design goals and completing the planned measurements. However, based on their experience with complex scientific experiments on the ground, several members remain skeptical about the large extrapolations required from ground testing to performance in space. This minority believes it likely that some as yet unknown disturbance may prevent GP-B from performing as required. The task group notes that in any event, should the GP-B experiment be completed successfully but yield results different from those predicted by general relativity, the scientific world would almost certainly not be prepared to accept them until confirmed by a repeat mission using GP-B backup hardware, or by a new mission using different technology.

Comparison with Other Proposed Programs

The scientific objectives of GP-B involve testing one of the fundamental laws of nature. The goals are therefore quite different from the objectives of a common situation in which natural laws, as inferred theoretically and tested in terrestrial laboratories, are used to interpret observations of astrophysical phenomena. In particular, the ambitions of GP-B are qualitatively different from those underlying most astronomical work, including NASA projects such as the HST, the Stratospheric Observatory for Infrared Astronomy (SOFIA), the Space Infrared Telescope Facility (SIRTF), and the Advanced X-ray Astrophysics Facility (AXAF). Tests of nature's laws are the ultimate

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foundation of physical science and are the only rational basis for belief that these laws are, at least in part, "understood." Despite its omnipresence, gravity remains the least well tested of all the fundamental forces.

NASA's highly successful COBE satellite was designed primarily to answer certain astrophysical and cosmological questions. Nevertheless, its results have implications in fundamental physics as well, particularly for questions concerning the origin of the universe. The task group's considered judgment is that the most likely of successful outcomes of the GP-B experiment—the measurement and confirmation of two specific effects predicted by general relativity--will be an important milestone, but will have less impact on the scientific world than the cumulative results of COBE. The reason is simple: there is no serious alternative to the general theory of relativity that predicts effects differing from those of general relativity by amounts that GP-B could detect. The GP-B experiment has been exciting for many scientists because of the need for confirmation of gravitomagnetism and the possibility of a great surprise, but the latter chance now seems more remote than before.

Other proposed satellite tests of frame dragging or spatial curvature, such as LAGEOS III, are intrinsically an order of magnitude less precise than GP-B. Another proposal claiming to offer higher accuracy is now in the conceptual stage and might eventually become a worthy successor to GP-B. It is discussed briefly in the section "Other Tests of Frame Dragging or Geodetic Precession" (pp. 10-12).

NASA estimates that $340 M will be required to complete the construction, launch, and data analysis phases of GP-B. If the experiment delivers as promised, so that the frame-dragging effect is measured to 1 percent accuracy and the geodetic term to 75 ppm, is it worth the cost? This question must be viewed in the context of other NASA projects of comparable magnitude, and necessarily its answer involves subjective scientific judgments. The task group was not able to achieve a clear consensus on the question of competitive value, even after extensive discussion and deliberation. Its members agree unanimously that all scientists would find it appealing to see a clean and direct demonstration of the frame-dragging effect, and that a confirmed discrepancy between the result of the GP-B experiment and the prediction of general relativity would fully justify the mission's cost, including the additional expense of a confirming experiment. However, in light of existing tests of gravitation theories such a discrepancy is considered highly unlikely.

Consequently, the task group's members hold a range of opinions on the relative cost-effectiveness of GP-B. A significant minority judge that the purpose of the mission is too narrow in comparison with missions that explore wide-open scientific issues and have a high probability of making new discoveries. This minority assigns high weight to the fact that essentially all experts believe that gravitomagnetism must exist, and consequently it does not appear likely that unexpected new knowledge will be gained.

In contrast, the task group's majority judgment gives higher weight to the importance of experimental verification in GP-B's unique and direct test of general relativity. Considering also the possibility of a revolutionary discovery, however remote, the majority judges the GP-B project well worth its remaining cost to completion.

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Scientific Motivation for GP-B

SIGNIFICANCE OF FRAME DRAGGING

Geometrical Viewpoint

Rotation and the Foundations of Physics.
Rotation has played a central, if problematic, role in the foundations of mechanics and dynamics. Although natural philosophers from Galileo to Newton had a clear understanding of the invariance of physical law in reference frames in relative rectilinear motion, the same could not be said with respect to rotational motion. Newton's famous "bucket" thought experiment illustrates the problem. Water co-rotating with a bucket climbs the wall of the bucket. Is this caused by rotation relative to absolute space, or relative to distant matter? If the bucket did not rotate, while distant matter rotated around it, would the same behavior result? Newton's gravitational theory was incapable of answering this question.

Despite the success of Newtonian dynamics in accounting quantitatively for the details of planetary motion, the tides, and local gravity, this conceptual issue remained unresolved. Interestingly, Foucault's 1851 demonstration that the plane of swing of a pendulum maintained a relation to the fixed stars while the Earth rotated underneath it caused a public sensation, and Foucault pendula quickly appeared throughout Europe and the United States. And while few physics textbooks today discuss the success of Newtonian gravity in explaining such phenomena as the advance of the lunar perigee, they do tend to discuss Foucault's pendulum.

The conceptual relation between local dynamics and distant matter was a central theme of Ernst Mach's formulation of a natural philosophy. In 1872, in *History and Root of the Principle of the Conservation of Energy*, he wrote:

If we think of the Earth at rest and the other celestial bodies revolving around it, there is no flattening of the Earth, no Foucault's experiment, and so on—at least according to our usual conception of the law of inertia. Now one can solve the difficulty in two ways; either all motion is absolute, or our law of inertia is wrongly expressed. . . . I [prefer] the second. The law of inertia must be so conceived that exactly the same thing results from the second supposition as from the first.

Mach's thinking influenced Einstein's development of general relativity. Although he later grew disillusioned with Mach, Einstein's conception of the law of inertia was meant to embody the loose collection of ideas now called Mach's principle. The resulting theory, general relativity, was not completely successful in that regard, yet it did ultimately succeed in resolving the issue of Newton's bucket. Ironically, that fact was not demonstrated until 1966, as discussed below.

Geometry and Frame Dragging. General relativity describes gravitation as synonymous with the effects of curved space-time. A "test" body (an electrically neutral body small enough to be unaffected by tidal forces) moves on a geodesic, the straightest possible trajectory, in the space-time around a gravitating body. Thus a satellite in orbit around the Earth (assumed non-rotating for the moment) describes a helical path in space-time (a circle in space, while moving forward in time) that for a single orbit is, say, 7000 km in radius, and 1.5 light-hours or 1.8 billion km long in the "time direction." Any portion of that space-time curve can be regarded as straight to high approximation.

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However, if the gravitating body also rotates, an additional geometrical effect, called frame dragging, should be present. There are a number of manifestations of this predicted effect. A particle released from infinity on the equatorial plane of a rotating body, moving initially in a radial direction (i.e., with zero angular momentum), will have its trajectory deflected away from a radial line so that it orbits the rotation axis in the same sense as the rotation of the body, all the while maintaining zero angular momentum. The period of a co-rotating particle in circular orbit about the rotating body is longer than the period of a counter-rotating particle orbiting at the same radius. Light rays sent around the equatorial plane of a rotating body (e.g., by the use of a ring of mirrors) take less time to return to a fixed point when they propagate with the sense of rotation of the body than when they propagate in the opposite direction. Finally, a gyroscope at rest outside a rotating body will precess relative to fixed objects at great distance. Since gyroscope axes define a local sense of non-rotation, local reference frames whose orientation is defined by gyroscopes rotate relative to frames fixed by distant objects.

Because geometry underlies all gravitational dynamics in GR, one can think of the effect just described as a "dragging" of the space-time geometry around the rotating body, much as a rotating cylinder causes a viscous fluid in which it is immersed to be dragged around in a whirlpool-like fashion. It is important to emphasize that this geometric effect associated with rotation is conceptually different from the static space-time curvature produced by a non-rotating body. The latter effect imprints itself on the external, far field of the source via the mass M, a scalar quantity (as in the limiting gravitational acceleration at large distances, given by GM/R^2). By contrast, frame dragging imprints itself via the angular momentum of the source, a pseudo-vector quantity $\mathbf{J}$.

Frame Dragging and Newton's Bucket. The existence of the frame-dragging effect suggests that rotation is not strictly absolute, but can be relational, that is, defined relative to other masses, just as is rectilinear motion. Although approximate solutions of the equations of general relativity for rotating bodies were obtained as early as 1918 (by Lense and Thirring, whence the alternative terminology "Lense-Thirring effect" for frame dragging), it was not until 1966 that an indication of this relational property of rotation was found. This result came from a theoretical analysis of the space-time in the interior of a slowly rotating, approximately spherical shell of matter. A hypothetical gyroscope at the center of the shell was shown to precess, and in the limit that the shell's gravitational radius $2GM/c^2$ tends to its physical radius (a condition corresponding loosely to cosmological values), the precession angular velocity tends to that of the shell itself. In other words, in that limit, gyroscope axes are locked to the distant matter constituting the shell. In 1985, further extensions of this work showed that, at the center of the shell, the requisite centrifugal forces would be induced by frame dragging, sufficient to cause water to climb the side of a "non-rotating" bucket, exactly in accord with Mach's stated preference. Consequently, within GR, rotation really is a relational concept, defined with reference to distant matter.

Thus frame dragging within general relativity has significant conceptual and philosophical implications concerning the relationship between local physics and the distant cosmos and the possibility of "absolute" space.

Gravitomagnetic Viewpoint

Another viewpoint on frame dragging exploits a similarity, in the weak-field, slow-motion limit, between general relativity and electrodynamics. Specifically, the space-time metric component $g_{00} \approx -1 - 2\phi/c^2 + \ldots$, which contains the Newtonian gravitational potential ϕ, is analogous to the scalar potential V of electromagnetism. The component g_{0i}, which has no correspondence in Newtonian gravitation, is analogous to the vector potential A_i (i varies over the spatial dimension). Associated with these potentials are a

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"gravitoelectric" field $\mathbf{E}_g$, a "gravitomagnetic" field $\mathbf{B}_g$, and equations of motion that approximately parallel the corresponding Maxwell equations and Lorentz force equation of electrodynamics. The spatial part of the metric g_{ij}, which relates to spatial curvature, has no counterpart in electromagnetism. It affects some of the equations but plays no direct role in frame dragging. This viewpoint also arises from treating general relativity at lowest order as a tensor (spin-2) field theory, analogously to treating electromagnetism as a vector (spin-1) theory.

In this approach, static matter generates a gravitoelectric potential g_{00} and space curvature g_{ij}, while moving matter generates in addition a gravitomagnetic potential g_{0i}. A rotating mass generates a gravitomagnetic dipole field, analogous to the magnetic dipole field of a rotating charge (apart from a numerical factor), and a rotating matter current (a gyroscope) external to the source experiences a torque ("spin-spin" interaction) analogous to that of a current loop in a magnetic field (apart from a sign change that reflects the attractive nature of gravity).

Gravitomagnetism and Lorentz Invariance.
In electrodynamics there is an intimate connection between electric and magnetic fields, resulting from Lorentz invariance. What appears to be pure electric field in one reference frame can be combined electric and magnetic field as seen in a reference frame moving relative to the first. General relativity is compatible with Lorentz invariance at its foundational level, and thus there should be analogous connections between gravitoelectric and gravitomagnetic effects. The field of a mass moving with uniform velocity v relative to an observer should be equivalent to that of a static mass as seen by an observer moving with velocity $-v$. The field of the moving mass contains a gravitomagnetic field generated by its mass current ($g_{0i} = -4v^i GM/Rc^3$). The field of the static mass contains only the gravitoelectric field g_{00}, and the spatial curvature $g_{ij} \equiv g_s\delta_{ij}$. Under a Lorentz transformation to the frame of

an observer with velocity $-v$, there results, to first order in v/c, $g_{0i} = -v^i(g_{00} + g_s)/c = -4v^i GM/Rc^3$. Thus, gravitomagnetism can be said to be related to gravitoelectrostatics through Lorentz invariance.

On the other hand, the gravitomagnetic field of a rotating mass *cannot* be obtained from the static field of a non-rotating mass by a simple rotation of coordinates, first, because such a rotating frame contains centrifugal and coriolis pseudoforces that distinguish it from a non-rotating frame, and second, because a rigidly rotating coordinate system cannot be defined globally, indeed can be defined only out to a radius at which the rotational velocity equals the speed of light. Thus, although some aspects of gravitomagnetism can be related directly to static gravity, frame dragging cannot be related to it so simply.

This result is consistent with the idea that frame dragging imprints the angular momentum J of the source on the distant space-time. A linearly moving source imprints both its mass M and its linear momentum p on the distant space-time; however, the latter can always be eliminated by a global Lorentz transformation to a frame in which the body is at rest ($\mathbf{p} = 0$). On the other hand, the angular momentum, like the mass, cannot be changed or eliminated by a global transformation.

Gravitomagnetism and Astrophysical Processes. The precession and forces associated with frame dragging have found important applications in astrophysical processes. Models for relativistic jets of matter ejected from the cores of quasars and active galactic nuclei invoke such frame-dragging forces acting on the matter and magnetic fields associated with accretion disks around rapidly rotating, supermassive black holes.

Frame-dragging effects also play an important role in the late-time evolution (the final few minutes) of in-spiraling binary systems of compact stars (neutron stars or black holes). That role includes precessions of the spins of the objects and of the orbital plane and contributions to the emitted gravitational radiation and the evolution of the orbital phase.

These effects are potentially detectable in gravitational wave signals received in the worldwide array of laser interferometric gravitational wave observatories currently under construction, including LIGO in the United States and a similar project called VIRGO in Europe.

SIGNIFICANCE OF GEODETIC PRECESSION

Geometrical Viewpoint

The geodetic effect is most simply viewed as a combination of a precession resulting from gravitoelectrostatics, and a precession related to curved space-time. A gyroscope in motion in the gravitoelectric field of a body experiences a precession that is described by the interaction of special relativistic corrections to the basic equations of motion with the external gravitoelectrostatic field, completely analogous to the effect in electrodynamics. This piece amounts to one-third of the total effect.

The remaining two-thirds of the effect comes from the curvature of space around the source. It can be understood by a two-dimensional analogy: on the surface of the Earth, transport a vector (a stick with an arrowhead lying on the surface) locally parallel to itself (i.e., not moving to the right or to the left) around a closed curve. If, for example, the curve consists of following the $0°$ line of longitude from the equator to the North Pole, following the $90°$ line of longitude from the Pole to the equator, and then following the equator back to the starting point, the vector will be found to have rotated by $90°$ relative to its initial orientation. This failure of a parallel-transported vector to return to its initial state on completing a closed path is the hallmark of curvature (indeed, this process is used in differential geometry to define the Riemann curvature tensor). Thus a gyroscope, whose axis can be shown to undergo parallel transport (provided that the gyroscope is in free fall), will undergo a change in its spin direction on completing each orbit in the curved space-time around the Earth. The precise amount turns out to be twice that of the gravitoelectric precession.

Gravitomagnetic Viewpoint

An alternative, purely gravitomagnetic, viewpoint works in the co-moving frame of the gyroscope, in which there is an apparent gravitomagnetic field of the source in linear motion ($-4v^{i}GM/Rc^{3}$), resulting in a precession analogous to that of a spin in a magnetic field. However, the net effect is reduced by 25 percent by the Thomas precession, which results from the fact that the co-moving frame of the gyroscope is actually a sequence of Lorentz frames with different instantaneous directions of the velocity, and whose axes therefore are rotated relative to each other. (The relative effect of Thomas precession here is smaller than in the electromagnetic case because of the factor of 4 that appears in the gravitomagnetic potential.)

GP-B AND OTHER TESTS OF GENERAL RELATIVITY

Experimental Gravity and General Relativity

Prior to 1960, the empirical basis of general relativity consisted of the Eötvös experiment, which verified the underlying equivalence principle, and two experiments that checked the theory itself: the deflection of light and Mercury's perihelion advance. The latter two experiments were regarded as being good only to 20 to 50 percent, and 10 percent, respectively.

Since 1960, however, significant progress has been made, both in improving the precision of existing tests and in performing new high-precision tests. This progress was enabled by the rapidly evolving technology of high-precision, high-stability, quantum-governed measuring tools, such as atomic clocks, lasers, and radio telescopes, together with progress in space exploration.

Improved tests were made of the Einstein equivalence principle, the foundation for the geometric viewpoint of gravitational theory. This principle is satisfied by general relativity and by all theories called "metric theories." These tests included improved tests of the composition-independence of free fall (Eötvös

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experiment: null tests to 10^{-12}), tests of spatial isotropy (local Lorentz invariance of non-gravitational interactions: null tests to 10^{-22}), and tests of the gravitational redshift (to 10^{-4}). It is worth noting that a satellite test of the equivalence principle (STEP) has been proposed that could improve the test of the composition-independence of free fall to the level of 10^{-17}.

The "classic tests" of general relativity were substantially improved: light deflection (using Very Long Baseline Interferometry, or VLBI) to 0.1 percent, and Mercury's perihelion advance to 0.1 percent. New tests were performed: Shapiro time delay in signal propagation (using Viking spacecraft tracking) to 0.1 percent; equality of acceleration of Earth and Moon toward the Sun (Nordtvedt effect) to 10^{-12} (translated to a 10^{-2} null test of relevant theoretical parameters). The Hulse-Taylor binary pulsar provided a test of the existence of gravitational waves in agreement with general relativity to 0.4 percent. Because the system contains neutron stars with strongly relativistic, nonlinear internal gravitational fields, the observations also provided indirect support for the theory in strong-gravitational-field regimes, through its prediction that such internal structure is effaced in the orbital and gravitational wave dynamics (by contrast with most alternative theories).

No previous experimental tests of general relativity directly probe the effect of frame dragging. Some effects of gravitomagnetism associated with translational motion of matter are present in such tests as the Nordtvedt effect, and in the orbital dynamics and gravitational wave emission of the binary pulsar, and some authorities have argued that the gravitomagnetic field has already been confirmed by indirect measurements. However, the gravitomagnetic effects in question occur in complicated combination with other effects, and so the gravitomagnetic contributions cannot be cleanly separated. No gravitomagnetic effects associated with rotation have ever been detected directly, in isolation from other relativistic gravitational effects.

Alternative Metric Theories of Gravity

Within a restricted class of alternative theories of gravity called metric theories, a useful framework has been developed, called the parameterized post-Newtonian (PPN) framework. It characterizes the weak-field, post-Newtonian limit of a substantial, though not complete, range of metric theories by a set of 10 parameters, γ, β, ξ, α_1, α_2, ..., whose values vary from theory to theory. Such theories generally contain, in addition to the basic space-time metric, auxiliary fields (scalar, vector, tensor, and so on) that mediate the gravitational interaction. The Jordan-Fierz Brans-Dicke scalar-tensor theory is the most famous example; recently, extensions of that theory have become popular in inflationary cosmological model building and in superstring-inspired gravitational theories.

In general relativity, $\gamma = \beta = 1$, while the other parameters vanish. Observations of the Shapiro time delay and of light deflection place the bound $|\gamma - 1| < 2 \times 10^{-3}$, and measurements of Mercury's perihelion advance combined with measurements of γ yield $|\beta - 1| < 3 \times 10^{-3}$.

Non-zero values for either of the parameters α_1 or α_2 signal the presence of auxiliary fields whose coupling to the distant universe produces local gravitational effects dependent on the local velocity relative to a preferred universal frame. Such effects appear as violations of local Lorentz invariance in gravitational interactions, and they produce anomalies in geophysics (Earth tides) and in orbital dynamics. Assuming that the solar system moves relative to the cosmos with the velocity 350 km/s, as determined from the dipole anisotropy of the cosmic background radiation, several bounds have been placed on the α parameters, specifically $|\alpha_1| < 4 \times 10^{-4}$.

In the PPN framework, the frame-dragging effect depends on the combination $1 + \gamma + \alpha_1/4$. The $1 + \gamma$ part comes from the connection between gravitomagnetism and gravitoelectro-statics via Lorentz transformations (in the PPN framework, $g_{00} + g_s = 2(1 + \gamma) GM/Rc^2$; see the section "Gravitomagnetic Viewpoint," pp. 6-8),

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and the α_1 indicates a possible violation of that local Lorentz invariance. Thus from this point of view, frame dragging tests the local Lorentz invariance of gravity. The bounds that have been placed on γ and α_1 are tighter in their implications for frame dragging than those GP-B can hope to achieve. It should be noted, however, that those bounds come from experiments whose conceptual basis is completely different from that of frame dragging and rely on an assumption about the relevant velocity that controls preferred frame effects. GP-B measures frame dragging directly.

The geodetic effect depends on the combination $1 + 2\gamma$. The first term corresponds to the gravitoelectric precession, the second term to the effect of spatial curvature; equivalently, $2 + 2\gamma$ comes from gravitomagnetic precession viewed from the gyroscope's frame, with a reduction of -1 from Thomas precession (despite the use of Lorentz transformations in this latter argument, α_1 does not appear). With a projected accuracy of 75 ppm in its measurement of the geodetic effect, GP-B offers a factor-of-20 improvement in the accuracy of the measurement of γ, from 2×10^{-3} to 10^{-4}. This is at the level where deviations from the exact unity value of GR could occur in a class of well-motivated, cosmologically important scalar-tensor alternative theories (generalizations of the Brans-Dicke theory), in which cosmological evolution following inflation naturally drives such theories toward but not all the way to equivalence with GR. Depending on the specific model, deviations from $\gamma = 1$ could lie between 10^{-3} and 10^{-7}. A bound from GP-B could constrain such models.

Wider Classes of Gravitational Theory

Metric theories of gravity whose post-Newtonian limits fit within the PPN framework represent only a portion of the "space" of alternative theories. This space includes metric theories that do not fit the PPN model, and the relatively poorly explored class of non-metric theories of gravity. It is fair to say that, should a breakdown of general relativity at the classical (non-quantum) level occur, it is likely to involve non-metric gravity and would lead to a radical conceptual revision of our view of gravity.

There is strong reason to suspect, from a number of different quarters, that non-metric revisions of GR at some level *will* be necessary. Unlike the other fundamental interactions, GR has a dimensional coupling constant and is not renormalizable in quantum field theory. The theory stands as a major stumbling block in the way of the unification of the interactions. In other words, physicists devoted to unification believe that GR must break down at some level. This is one of the greatest challenges of modern theoretical physics. It is generally assumed, though not proven, that the failure of GR will occur at the level of quantum gravity, far from the regime of observable effects that can be tested by local experiments. On the other hand, examples exist of unification-induced modifications of GR (in superstring-inspired theories, for instance), in which residual effects do occur at the classical, detectable level of cosmology.

Non-metric modifications of GR could still be viable, provided they are compatible with the high-precision experiments that check the Einstein equivalence principle underlying metric gravity. (One motivation for proposing experiments such as STEP is to provide dramatically improved tests of this principle and thereby to test for the effects of such modifications.) Within this broader class of theories, no conclusion can be drawn about prior bounds on frame-dragging effects from other experiments such as light deflection, time delay, or tests of local Lorentz invariance. On the other hand, there are currently no examples of non-metric theories that agree with all local observations and yet predict a detectably different frame dragging.

OTHER TESTS OF FRAME DRAGGING OR GEODETIC PRECESSION

There has been no prior, direct test of general relativistic frame dragging. Apart from GP-B, the leading current proposal for a

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possible future test is LAGEOS III, a third laser-ranged geodynamics satellite launched into an orbit whose inclination is supplementary to that of LAGEOS I or II. The frame dragging induced by the rotation of the Earth causes a precession of the orbital planes of both satellites (the orbits are in effect gyroscopes); the use of two satellites with accurately supplementary inclinations permits the cancellation of the 10^7 times larger, but equal and opposite precessions induced by the Earth's Newtonian multipole moments. At best, this proposed experiment would yield a 10 percent test of frame dragging. It has not been approved for launch by any space agency at present.

Other less promising or less fully developed proposals include detecting the gravitomagnetic contribution to gravity gradients, as measured by orbiting superconducting gravity gradiometers; measuring the precession of the plane of a Foucault pendulum erected at the South Pole; and measuring the precession of orbiting non-cryogenic gyroscopes by optical means. A recently published proposal (B. Lange, Phys. Rev. Lett. 74, 1904 (1995)) based on the latter idea would use an autocollimator to sense the orientation of an unsupported gyro, thus giving it the working name AC-USG. The design of such a project is still at the conceptual stage, but it is claimed that it could be much more accurate than the present GP-B design. The natural angular sensitivity of an optical autocollimator is far better than that of a readout based on the superconducting London moment; the single gyro in AC-USG would be in a drag-free environment, with a much larger spacing between gyro and housing than in GP-B; the spacecraft would roll around the gyro axis rather than around the direction to the reference star, thereby minimizing a certain class of spurious torques; and two counter-orbiting satellites could be used to largely cancel some other kinds of errors. Despite these apparent advantages, it is too soon to say whether the AC-USG could work as claimed. The error analysis of the GP-B is the result of decades of work, many Ph.D. theses, and detailed engineering designs, and a similarly thorough and cautious approach would be needed for AC-USG. Consequently,

the task group could not assess its claims quantitatively or discuss the budget for such a project; but if future scientific developments require a better measurement of gyro precession, this approach could be a promising one.

One test of geodetic precession has been reported, namely that of the lunar orbit (viewed as a gyroscope) in the field of the Sun, measured using lunar laser ranging combined with VLBI data (see B. Bertotti, I. Cinfolini, and P.L. Bender, Phys. Rev. Lett. 58, 1062 (1987) and I.I. Shapiro et al., Phys. Rev. Lett. 61, 2843 (1988)). The result agrees with general relativity to about 2 percent. In the Hulse-Taylor binary pulsar, the effect of frame dragging of the pulsar's spin axis caused by the spin of its companion is too small to be detected. There is, however, a potential precession of the pulsar's spin caused by a combination of the gravitomagnetic field generated by the companion's orbital motion (relative to the center of mass), together with the companion's gravitoelectric field and the resulting space curvature, through which the pulsar moves. Although a very significant secular change in the radio pulse shape has been observed (an effect not observed in other pulsars), given the uncertainties in the structure of the emitting region of pulsars, it seems unlikely that such measurements will ever yield results better than the results of the lunar test of the geodetic effect, much less those of GP-B.

Geodetic precession is sensitive to the value of the PPN parameter γ. VLBI measurements of the deflection of light are unlikely to reach below the GP-B level of 10^{-4} in $(1 - \gamma)$. No planned or proposed interplanetary probes will have the requisite tracking capability to measure the Shapiro time delay to higher accuracy than has been done. Planning for orbiting optical interferometers with microarc-second accuracy and the capability to improve light deflection measurements by 2 or more orders of magnitude appears to have halted. The European Space Agency has plans for a successor to the Hipparchos mission, the Global Astrometric Interferometer for Astrophysics (GAIA), with 20-microarc-sec accuracy, which could measure

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light deflection and γ to 10^{-4}. Although this accuracy would be comparable to that of GP-B, this mission is unlikely to fly before 2006. Thus on the 1999 to 2000 time frame of GP-B, there is unlikely to be a competitive measurement of space curvature via the parameter γ.

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Essentials of the GP-B Experiment

As described above, the geodetic and frame-dragging effects of relativistic gravit should cause the spin axis of a g roscope in Earth orbit to precess. In a polar orbit the geodetic term is orthogonal to the frame-dragging term, and about 160 times larger. General relativit predicts the precession due to frame dragging to be about 42 milliarc sec/yr, or 1.2×10^{-5} deg/yr. The measured precession is expected to be 30 to 40 milliarc sec/ r, depending on the orbital altitude and the celestial declination of the chosen reference star. In order to be sensitive to such a tiny effect, the experimental strategy of GP-B is to use a drag-free satellite to minimize extraneous forces as much as possible, and to make the g ros and sensors superconducting for low noise. For redundancy four gyros are planned (two pairs made of different materials and spinning in opposite directions), with their axes pointing to the reference star. The aberration angle of the reference star varies throughout the orbit and the year, providing precise calibrations of convenient magnitude.

$\Delta\theta = 6.6$ sec/yr (GEODETIC)

GUIDE STAR

$\Delta\theta = .042$ sec/yr (FRAME DRAGGING)
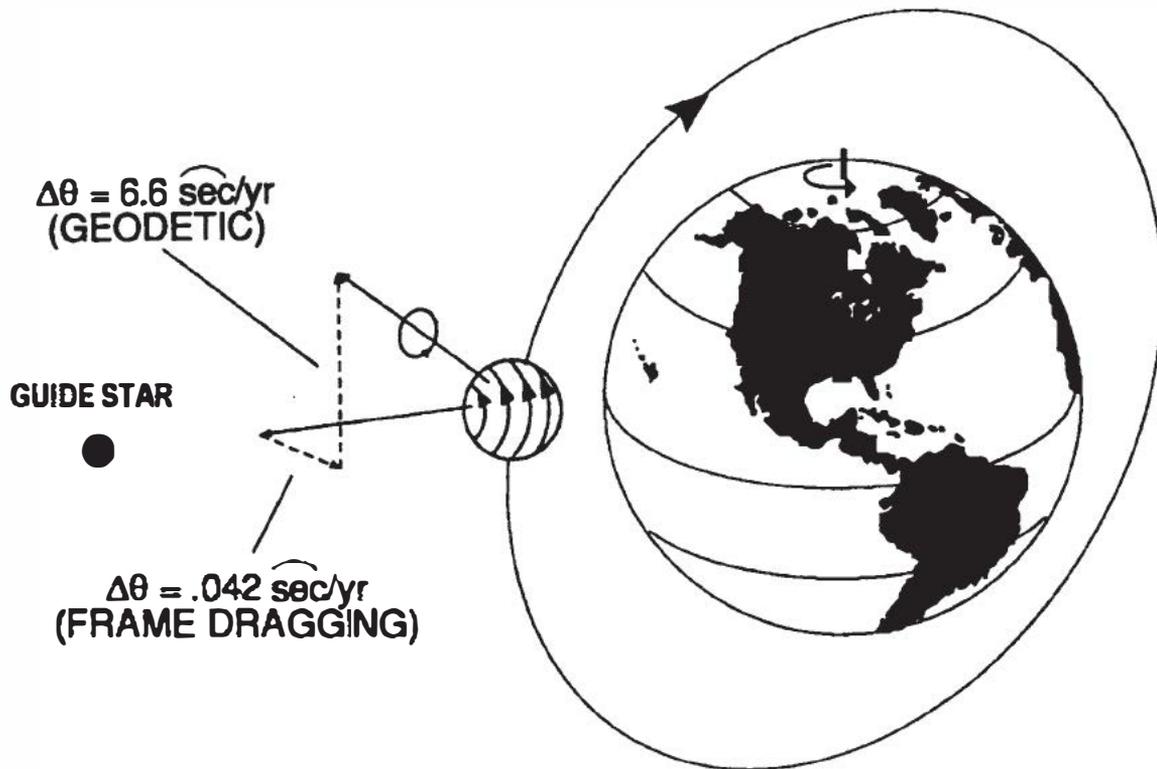
Figure 1. Gravity Probe B involves a precision gyroscope in low polar orbit and a small telescope locked onto a distant guide star. The geodetic and frame-dragging effects of relativistic gravity are expected to cause the gyro's spin axis to precess as shown throughout a yearlong experiment.

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CRYOGENIC INSTRUMENTATION

The GP-B gyroscopes rely on a number of unique phenomena found in superconductors. These include the generation of a magnetic field when a superconductor rotates (the London moment), and the exclusion of magnetic flux changes from the interior of cylinders and rings of superconductors (the Meissner effect).

London Moment

In the 1950s Fritz London produced a remarkable body of work on superfluids and superconductors. In his classic analysis of the symmetries related to superfluid phenomena, he discussed the quantization of circulation of flow and the related quantization of magnetic flux contained within superconducting cylinders, in integral multiples of the flux quantum $\Phi_0 = hc/2e \approx 2 \times 10^{-7}$ gauss cm^2. (Here h is Planck's constant, c the speed of light, and e the charge of the electron.) In addition, he predicted the generation of a magnetic moment by a rotating superconductor.

London showed that electromagnetic coupling between the positive ions in a lattice and the superconducting electrons would produce a magnetic field in the interior of a spinning superconductor. The magnetic moment of a rotating sphere has a number of ideal properties for indicating the motion of a gyroscope. The field is directed along the spin axis and is independent of the specific material properties of the superconductor. Unfortunately, the London moment is numerically small, providing a field of only B $\approx 10^{-5}\omega$ (in units of gauss), where ω is the spin frequency. Accurate tracking of the spin axis of a gyroscope using the London moment requires unusually sensitive measurements of changes in magnetic flux, together with a related set of designs and procedures to safeguard against spurious magnetic signals.

Spin Readout

Changes in orientation of the spin axes of GP-B's science gyroscopes are detected with a superconducting quantum interference device, or SQUID. The heart of a SQUID is a superconducting ring containing two Josephson tunnel junctions. When the magnetic flux through the ring changes, a current flows in the metal. The current flow produces a DC voltage across the pair of tunnel junctions. By using transformer coupling to the SQUID, magnetic flux signals from any number of sources can be imposed through the superconducting ring. Modern SQUIDs can detect modulated flux changes smaller than 10^{-6} Φ_0 in 1 sec. The SQUIDs developed for GP-B are state-of-the-art devices designed to yield optimal signals, and they have very weak magnetic coupling to the motion of the gyroscope itself. A great deal of thoughtful and creative effort has gone into the design of the electrical coupling to the SQUIDs and their shielding from environmental influences.

In the configuration used in GP-B, the SQUIDs are used as null detectors. A change in orientation of a gyroscope's London moment produces a current in a superconducting loop surrounding the sphere. That current is coupled to the SQUID by a transformer that induces a secondary current in the ring. This current produces a voltage that can be measured by external electronics. The null operation is achieved by feeding a small current back to another transformer circuit that couples the magnetic field into the SQUID ring. The sense and magnitude of the feedback current are arranged to cancel the voltage drop across the Josephson junction. A SQUID configured with such a servo-controlled current is said to be "flux-locked," since the scheme keeps the magnetic flux through the SQUID constant. The null detection method is very important to the gyroscope readout of GP-B, because it is intrinsically linear.

Operation of the SQUIDs and of their associated electronics has been thoroughly tested in conditions similar to those of the space mission. The sensitivity and long-term stability of the devices appear to be more than adequate for making the desired measurements of gyroscope precession. There is, moreover, an important redundancy in the design. Eight separate SQUID detectors are provided for the four gyroscopes. Despite the apparent

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complexity of the technique, it seems quite unlikely that a failure in the SQUID circuits will jeopardize the experiment.

Stray Magnetic Fields and Trapped Flux

The elegant principle involved in measuring the orientation of the London moment has one major difficulty: the moment itself is very small. In order for the desired signal to dominate, other sources of magnetic fields must be removed to an extraordinary degree. Superconductors trap the ambient field when cooled through the normal-to-superconducting phase transition. If the superconducting gyroscope surfaces trap even very small amounts of magnetic flux, thereby producing signals much larger than those related to the London moment, the experiment could be doomed. Although the effects of small remnant trapped fields may be effectively removed during later data analysis, signals from large quantities of trapped flux would dominate the SQUID readouts and render the desired data interpretation impossible.

Several measures have been taken in the design of GP-B to remove unwanted magnetic fields. The first relies on another property of superconductors. The amount of flux trapped within a superconductor is quantized in integral multiples of Φ_0. The relevant procedure, devised through careful experiments by the GP-B group over the past 30 years, involves the exclusion of magnetic flux from the interior of a superconducting cylinder by sequential expansion of superconducting lead shields. After many repetitions, such a process could lead to a region with no magnetic field. The enclosure within the Dewar housing the GP-B gyroscopes has the final lead shield following multiple applications of the lead-bag expansion technique. Each step of shielding excludes flux by the ratio of the initial to final area of the expandable bag. In principle, even the last quantum of flux can be removed. The method has been developed by the GP-B group to a point where it is quite reliable. The initial magnetic field for the apparatus can be quite small indeed. The only problems related to

trapped ambient flux are likely to come from magnetic fields associated with the support apparatus for the gyroscope, or those that arise when the spheres are cooled.

Another important problem related to residual magnetic flux is that associated with the gyroscope sphere itself. Even in conditions of zero external magnetic field, superconducting bodies frequently produce significant trapped fields as they are cooled through the superconducting transition. Small thermal gradients in the metal at the time of the phase transition produce thermoelectric currents in the metal. Magnetic fields from such currents become trapped in the final superconducting state. In order to avoid such effects, great care must be taken in "annealing" the metal into its final state. Thermal gradients in the sphere at the transition temperature must be very small. Thermally induced magnetic flux in the superconducting spheres of GP-B has been measured and satisfactorily removed through sequences of repeated slow cooling through the superconducting transition. Relevant tests on the final apparatus can be conducted on the gyroscope spheres after they have been cooled to low temperatures, prior to launch of the satellite. The GP-B team has made careful studies of these phenomena, and it seems likely that trapped flux can be eliminated from the apparatus used in the experiment.

With regard to materials used in the apparatus, extensive tests and measurements have been made of all components located inside the lead shield. Some materials have been rejected because of their residually small (but still undesirable) magnetic properties. Only those components with innocuous magnetic properties have been retained in the final design.

Reliability

The low-temperature portion of the apparatus for GP-B is exceptionally complex. Many interrelated systems must work without recourse to room temperature recycling for repairs. Although the task group has found no obvious flaws in the concept, design, or ground tests of the apparatus, it notes that success of the

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GP-B experiment requires a sizable number of separate state-of-the-art devices to work correctly and simultaneously.

The gyroscopes are sensitive to torques thousands of times smaller than any that have been previously measured. This, the most critical aspect of the experiment, cannot be tested in normal gravity at the Earth's surface. Full sensitivity can be obtained only in conditions of near-zero effective gravity. As with any instrumentation attempting such a large jump in sensitivity, unanticipated problems or even new physical phenomena could interfere with the desired measurement of torques on the gyroscopes.

THE GENERATED SIGNAL

The London moment of each spinning gyro in GP-B is sensed by a pickup loop in a plane containing the star-tracking telescope axis. Along with the rest of the satellite, the loop rolls about that axis at a low (0.004-Hz) frequency. Any misalignment between the gyro and telescope axes is kept small, ≤ 100 arc sec. Since the gyro axis and the normal to the loop are nearly perpendicular, the London flux through the pickup is proportional to the small misalignment angle, corresponding to a magnetic field of the order 10^{-13} gauss. This flux is modulated at the roll frequency. The pickup loop is part of the superconducting primary circuit of the transformer in a DC SQUID magnetometer, the remainder consisting of the SQUID input coil. Conservation of magnetic flux through the primary circuit is maintained by a current in the transformer's secondary circuit. The resulting output signal is a voltage proportional to that of the secondary current. With two pickups on each of four gyros, eight such voltages are digitized and recorded with 16-bit precision.

Magnetometer signals appear also at other frequencies. Flux quanta trapped in the superconducting gyro rotors produce signals modulated at the spin frequency, around 125 Hz. The motion of the rotor's spin direction in its own body frame, called "polhoding," produces flux variations at the spin frequency,

multiplied by a tiny factor arising from the 10-ppm fractional difference in the gyro's principal moments of inertia. Aberration of light from the reference star occurs both at the satellite's Earth orbital frequency and at the annual frequency of motion around the Sun. These aberrations are manifested as apparent precessions of the gyro axes at those frequencies. Also modulated at the satellite's Earth-orbital frequency and its harmonics are other effects, including periodic occultation of the reference star by the Earth.

The effects of relativistic gravity to be measured in the GP-B experiment include the 6600 milliarc sec/yr geodetic precession of the gyro axis in the satellite's polar orbital plane, and the frame-dragging precession, amounting to 42 milliarc sec/yr normal to that plane. Additional effects include a 7 milliarc sec/yr correction arising from the orbital eccentricity about the oblate Earth and a 19 milliarc sec/yr geodetic precession caused by the Earth's orbit around the Sun. Absolute calibration of the magnitude of the gyroscope precession signal will be achieved by comparing it to the signals caused by aberrations of the reference star.

Because the spacecraft rolls about the reference-star axis, separation of the frame-dragging and geodetic effects requires absolute determination of the roll phase. The goal of a 0.1 milliarc sec/yr contribution from this source to errors in the frame-dragging measurement requires determining the roll phase to 3 arc sec. Although it is monitored by an auxiliary "star blipper" telescope, the roll phase will be determined primarily by analysis of the reference-star aberrations mentioned above. The important role of annual aberration in this analysis severely bounds the time interval over which data must be acquired. For example, the GP-B experiment can be as much as five times more precise after 1 year of data collection than after 6 months.

During the extended data acquisition period of GP-B it will be desirable to update the analysis frequently. For this purpose an intermediate set of variables has been defined, in terms of which the analysis is linear. This makes possible the optimal use of a recursive

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Kalman filter for updating the experiment's status. Obtaining the quantities of ultimate interest requires a subsequent nonlinear analysis that can be done periodically. The performance of the relevant software, and of a significant portion of the GP-B hardware and data acquisition system, has already been tested by simulating the expected input signals to the SQUID and exercising the readout and analysis sequence.

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Systems Engineering Assessment

SPACE VEHICLE

The present design of the GP-B space vehicle, which combines the science payload with a host spacecraft, has evolved over a long history dating back to the late 1960s. In addition to the normal mission objectives and launch-vehicle constraints imposed by NASA, requirements were also imposed for a set of fundamental measurements and constraints critical to the scientific goals. The vehicle requirements in turn have been allocated among the various subsystems and their hardware and software elements. The allocations were made by using a systems engineering procedure that includes feedback from the specific design criteria necessary to meet each requirement, combined with a comprehensive analysis of the contribution to the total expected measurement error from each candidate design.

The GP-B project had an unusually long period (more than 10 years) from early conceptual design through the preliminary design phase. In this interval the design team was able to develop new technologies, validate critical functional and hardware criteria, and assess their impact on the experiment. The extended development phase has allowed trade-offs among error sensitivities and design margins in order to balance risks over the whole program. The resulting development procedure for the spacecraft and its integrated payload has involved extensive prototyping of each selected element and subsystem, as well as demonstrations of most of the difficult integration processes.

At the time of the task group's review, the prototyping and integration work had demonstrated the validity and completeness of design criteria imposed to meet system requirements, as well as an ability to control the spacecraft hardware over a range of imposed environments. Final configurations of flight

hardware have been established by using this foundation of experimental input to the systems engineering process. The GP-B requirements, design criteria, configurations, and interfaces now exist as a controlled database maintained at Stanford, Lockheed, and NASA, with elements as appropriate at selected subcontractors. The space vehicle subsystems are being developed to meet a set of hardware and software specifications derived from the allocated requirements by several "integrated product teams." Each team is composed of key experts selected and assigned from the personnel at Stanford, Lockheed, and major subcontractors. This approach helps to streamline the information flow, decision making, task direction, and execution and has recently come into favor at NASA. (For example, it is being implemented within the revised space station program.) The approach has been used very effectively by the GP-B project for several years.

Spacecraft Structure

The open-frame welded construction of the spacecraft permits maximum radiation from the Dewar shell to space. It also eliminates joint motion and can be machined to the precise interfaces required. The structures of the solar array panels are made of graphite epoxy and have a low coefficient of thermal expansion. This minimizes thermal shock at the day-night boundary, thereby eliminating a class of disturbing torques. Critical components of the release and deployment mechanisms for the solar array are flight-qualified and redundant. The important mechanism for trimming the spacecraft center of gravity is now in the incremental prototype phase and is expected to be finished by mid-1995. The design has adequate control authority to handle any

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plausible configuration and operational conditions.

Electrical Power

Peak power tracking is used to maximize the useful power from the solar arrays. A single nickel-cadmium battery unit (of two available) can support the mission. Most of the power subsystem hardware is already flight-proven, and only minor modifications are being made.

Communications

The communications subsystem is designed around flight-qualified hardware, including S-band links to the tracking and data relay satellite system (TDRSS) and redundant forward- and rear-facing antennas. Adequate data-rate link margins of 3 decibels have been incorporated.

Attitude and Translational Control

Proper operation of the attitude and translational control (ATC) subsystem is crucial to the scientific success of the mission. Primary pointing requirements are met with the proven fine-guidance system from the Hubble Space Telescope; its architecture and built-in protective measures have been well demonstrated under continuous operation in space. Backup or optional attitude control can be achieved without the gyros by using the helium thrusters described below. Other functions performed by the ATC subsystem include backup attitude and pointing using control gyros and magnetic torque rods, orbit injection and trim using GPS and/or star sensors as references, precise roll control, and position readout to 10-arc-sec accuracy.

Very-high-precision translation control is required to provide a zero-drag environment for the precision gyros and proof mass. The translation thrusters make use of the helium gas slowly boiling out of the Dewar. The same system also maintains pressure by ejecting gas in a controlled, nearly isotropic manner. The desired thrust is produced by differential flow control through a set of low-expansion-ratio nozzles. These thrusters and their proportional

control incorporate a new design, not yet proven in flight. One of the critical requirements to be met is adjustment of the sensitivity of individual thrusters to variations in inlet gas conditions. This sensitivity arises in part from the very low gas stagnation pressures, absolute temperatures, and Reynolds numbers in the nozzle. The design makes use of a nozzle-inlet pressure feedback to control a continuous flow into each thruster. The design criteria have been refined and validated in two development models, and a prototype engineering unit has been extensively tested.

Integrated Payload

The integrated payload consists of the Science Instrument Assembly (SIA), the probe, and the Science Mission Dewar (SMD). The SMD also forms a major structural element of the space vehicle itself. Component specifications, interfaces, and total configuration for the integrated payload were essentially complete at the time of the task group's review. Current activities are directed toward completing the verification testing of the component and subsystem hardware and addressing the cryogenic integration procedures.

The instrument package known as "Probe B" will be integrated into a ground-test Dewar early in 1995 (minus the telescope element in the SIA) and will undergo a series of design verification tests. In 1996 this probe will be upgraded with a flight-design telescope and reintegrated into the final SMD. The resulting integrated payload unit will then undergo a rigorous qualification program. Rotating it to a horizontal position will permit checkout of spin-up and caging of the science gyros in that orientation, for comparison with their vertical orientation characteristics. The flight unit will have its critical design review in the spring of 1995, and flight hardware is to be delivered in October 1996.

The SMD must provide a uniform very low magnetic field environment (10^{-7} gauss) for the probe and the SIA. It must maintain enough liquid helium capacity for the cryogenic needs of the SIA and still provide the required gas

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flow to the ATC thrusters over an operating period of up to 20 months. The task group notes, once again, that the available operating time for the experiment is one of the most important parameters determining the experiment's overall accuracy.

RISK ANALYSIS

One of the major objectives in this review is to appraise the risk that GP-B might not make an accurate measurement of the relativistic precession of a gyroscope in Earth orbit. The task group studied the objectives, design, analysis procedure, test data, and operational plans for the experiment. Using this information, and based on individual members' backgrounds in science and/or space missions, the task group arrived at varying opinions from which a consensus was formed. Summarized here is much of the information on which the group's risk assessments are based.

Overall Credibility

The scientific goal of GP-B requires putting gyros in Earth orbit with unmodeled spurious drifts no greater than 0.5 milliarc sec/yr. Before addressing the risks in achieving this spectacular performance, the task group lists some of the particulars that help to make the experiment credible:

1. Each of the four spinning gyros is a nearly perfect sphere of uniform density, operating in almost ideal free-fall conditions. Disturbances caused by atmospheric drag and other non-gravitational forces are eliminated exactly for one gyro. This is achieved by using small active thrusters to keep the case from contacting the spinning sphere, which is unsupported. With additional active control loops, the other three gyros, located close to the first, are individually given minute electrostatic supports to account for the small relative accelerations and gravity gradients. Because the support forces are tiny, the disturbing torques and gyro drifts should be tolerable.

2. To minimize any sensitive misalignments of axes, the cases of the four gyros and the reference-star telescope are made from single blocks of fused quartz. By thin-film cementing of the gyro and telescope blocks over their flat mating surfaces, the critical parts of the experiment are made into a single stable structure.

3. The quartz-block assembly and its readout electronics operate at liquid helium temperature, thus providing a number of essential properties: low mechanical creep, low thermal gradients, superconductive shielding of disturbing magnetic fields, ultrahigh vacuum to avoid disturbing torques on the gyros, and low-noise angular readouts of the reference-star telescope and gyros.

4. The spacecraft axis is nominally pointed at the reference star and given a controlled roll of about 0.25 revolutions per minute. Small misalignments of the individual gyro axes, the telescope axis, and the reference-star direction produce signal modulations at the roll frequency with amplitudes proportional to the misalignments. As long as the misalignments do not change significantly over the roll period, the signal can be processed to determine the misalignments and, in particular, the precise angle of each gyro axis from the reference star. Rapid changes in the quartz-block assembly would cause readout errors while such changes were happening, but such unlikely and occasional events could be readily identified and eliminated from the data.

5. The spacecraft roll helps in another way. Because many possible sources of spurious torques are tied to the case of the gyro, the direction of gyro drift correlates with roll phase and the net drift averages to zero over an integral number of roll cycles.

6. Aberrations caused by the Earth-orbital and annual motions of the spacecraft modulate the apparent direction of the reference star. The amplitudes, periods, phases, and directions of these aberrations are known very precisely. In

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the GP-B data they will have signatures similar to those of the relativistic precessions. Because they are precisely known, they will not conceal the desired information; instead, the aberrations provide a built-in precise calibration of the gyro and telescope readouts that is continuously available throughout the mission.

7. If not measured independently, proper motion of the reference star during the experiment could limit the accuracy of the experiment. Consequently the proper motion will be determined by a new and very accurate technique. The selected reference star will be chosen to be bright enough for the GP-B telescope, detectable as a point radio source, and close in direction to a distant quasar. Changes in the star-to-quasar angular separation will be measured by VLBI, thus yielding the proper motion of the reference star with high accuracy.

Hardware Failure

The task group considers two possible kinds of failure of the GP-B experiment: a clear hardware malfunction leading to no credible measurement of gyro precession, and a failure to achieve the target accuracy of 0.5 milliarc sec/yr. Outright failure is a risk common to all space missions. However, much of the GP-B experiment's design and implementation has already been proven in flight. In particular, nearly all parts and functions except the science instrument package are identical to or derived from those of the Hubble Space Telescope (which was designed and built by the same Lockheed contractor team). Therefore the non-science part of GP-B should pose a smaller risk than did the more complex HST system when it was launched. The translation control for achieving local drag-free conditions has been successfully proven by the Navy's Transit navigation satellite. The control gyros that failed in the HST can be excluded from consideration because in GP-B they have been replaced by an entirely different design of proven reliability. The workhorse Delta launch vehicle and its operation are judged as having a

low risk of failure for similar (if not stronger) reasons.

The most important concern, therefore, is the risk of failure in the GP-B science package and its supporting cryogenics. Included here are the four high-precision gyros, the reference-star telescope, the associated cryogenics and electronics, and the spacecraft translation and rotational controls that differ from equivalent HST functions. The functional reliability of the science payload depends in the first place on excellent engineering design and proven practices for the manufacture, test, and analysis of all subsystems. The task group has not identified any serious weakness in these areas; indeed, it is highly impressed with the thoroughness of attention to detail reflected in answers to its questions and the extensive documentation supplied. The functional reliability of GP-B also depends on multiple hardware and operational redundancies. The four gyros each have redundant suspension and readout electronics, as do the telescope readouts for each axis. In fact, functional redundancy throughout the spacecraft is such that most single-point failures can be tolerated. The hardware configuration of redundant operational alternatives is fully controllable from the ground.

Dropouts of the gyro and telescope data can be tolerated over significant intervals without fatally compromising the experiment. Indeed, the telescope data are necessarily unavailable for half of each spacecraft orbit, due to occultation of the reference star by the Earth. Even with more serious and unintended dropouts, if the redundant support systems do not fail the gyros will continue to "remember" their precessions from the beginning of the yearlong experiment, and subsequent readouts can largely supersede the missing information.

Probability of Achieving the Desired Accuracy

Many factors contributing to the final experimental accuracy are testable on the ground at the component and subassembly level. These items, insensitive to the effects of weight

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and having been demonstrated stable, should operate reliably during the mission. Performance degradation, if it occurs, can be identified and either corrected or compensated for to the required level by any of several means.

However, such avenues can do nothing to avoid degraded accuracy caused by spurious torques on the gyros. Such torques could arise from many possible causes, and they might not be reduced sufficiently by roll averaging. Adequate control of disturbing torques is fundamental to the success of the experiment, and it cannot be demonstrated on the ground because relatively large electrostatic forces are then required to support the gyros. These supports cause correspondingly large spurious torques and consequent gyro drifts—drifts that would not exist in the free-fall conditions in orbit. Disturbing torques that might spoil the measurement in orbit are "lost in the noise" on Earth and cannot be observed or evaluated by their effects on gyro precession.

The GP-B team has made an extensive theoretical search and analysis of known phenomena that could be candidates for spoiling the experiment's accuracy. The considered list is a long one; moreover, the GP-B project has had many critical and comprehensive reviews over its long history. In these reviews no specific phenomena have been suggested that have not been proven negligible or acceptable in the overall error budget. Nor has anyone been able to fault these analyses. Needless to say, all reviewers are motivated as a matter of pride to identify new phenomena of possible concern. Nevertheless, the possibility of a new and fatal problem area cannot be ruled out by such arguments.

A commitment to launch GP-B must depend on the level of confidence remaining after allowing for concerns such as these. It is important to note that most of the tests the GP-B team would like to have performed on Earth, but could not, can be performed in orbit—before, during, and after the yearlong science experiment. An extensive plan for such measurements has been prepared, and the plan will be exercised in laboratory simulations using real hardware wherever possible. These simulations could confirm much of the pre-flight analysis of anticipated phenomena; they might also help to identify unanticipated sources of error and perhaps even point the way toward recovering lost experimental accuracy under some conditions.

Two powerful approaches are planned for the in-orbit tests. A series of measurements at low gyro spin frequency will be made to amplify the effects of disturbing torques. Other tests will involve explicit changes in various operating conditions, to confirm or expose their influence on the observed gyroscope precessions. Either or both techniques could reveal and calibrate a large class of anticipated and unanticipated effects that might otherwise remain hidden. Detection and measurement of a surprisingly important effect might suggest more favorable operating conditions or some other kind of accuracy-saving compensation.

The task group notes that the four gyros are made of amorphous quartz or crystalline silicon, in paired combinations with clockwise and counter-clockwise spins. Each gyro is therefore unique. This design feature was motivated by the possibility that an unexpected new effect might exhibit different signatures in one or more of the gyros. Obviously, such a result could provide further assistance with the identification and diagnosis of problems.

Sensitivity of Experimental Errors to Key System Parameters

The task group asked a number of questions of the project management to help it assess quantitatively the risk of not achieving the design-goal accuracy of 0.5 milliarc sec/yr:

1. What are the sensitivities of the standard errors of the frame-dragging and geodetic precession measurements to key hardware design and operating parameters?

2. What are the margins of these key parameters relative to their design-allocated values?

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3. What are the parameter values, either currently demonstrated or estimated, for likelihoods of 84 percent and 99.9 percent of being "better than or equal to"?

4. What is the margin in meeting the 0.5 milliarc sec/yr standard-error requirement, based on a parameter set containing the most probable values and another set using the 84 percent likelihood values?

5. If the most critical parameters do not meet their likelihood profiles, will the experimental error degrade gracefully?

In responding to these questions the Stanford group identified 19 key hardware and operating parameters, 5 of which are especially critical to achieving the GP-B science objectives. Calculations were made to assess the impact of degrading any or all of the parameters from their currently estimated, most probable values. With the 14 noncritical parameters set at their conservative 3σ values (one-sided 99.9 percent confidence limits), and the remaining 5 set at their most probable values, the geodetic and frame-dragging standard errors are estimated to be 0.20 and 0.18 milliarc sec/yr, respectively, for each of the four gyros individually. Uncertainty in proper motion of the guide star is common to all four measurements, but the total errors are dominated by effects that are uncorrelated among the gyroscopes. Taking this into account and assuming that there is adequate consistency among all four gyros, the team estimates a most probable 1σ experimental error of about 0.11 milliarc sec/yr.

A more conservative approach uses the likelihood profiles for all 19 system parameters and yields an 84 percent probability of achieving standard errors for the geodetic and frame-dragging coefficients of 0.36 and 0.31 milliarc sec/yr, respectively, for each gyroscope individually. Again the largest contributions are expected to be uncorrelated, and so the total experimental error should be nearly a factor of 2 smaller.

Analysis shows that the standard errors degrade gracefully for all but 2 of the 19 parameters: gyro-readout nonlinearity, and root-mean-square pointing error on the guide star. However, sizable margins exist for these quantities (currently factors of 10 and 2, respectively) between their 3σ values and the points at which they become a problem. The instrument team points out that these error analyses are based on current experimental data, without regard for expected improvements. As they move forward in their verification program, they expect many of the parameter values to be tightened up in the favorable direction.

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Concluding Observations

It is the unanimous opinion of the task group that Gravity Probe B is an extraordinarily well designed experiment. The science instrument design is very well conceived to minimize every known category of error. The spacecraft will roll around an axis passing through the gyros, so that all torques generated by the suspension system and the spacecraft average out to high accuracy. The instrument package has extensive redundancy to guard against individual failures, and in order to protect against more general failures the redundant units are not all identical. The instrument and spacecraft are designed as far as possible with the flexibility of laboratory equipment, including remote adjustments for every important parameter and the equivalent of a portable oscilloscope able to examine every important waveform.

GP-B is a highly complex experiment, one that must work properly in orbit for many months. A majority of the task group believes that a credible analysis of expected errors has been performed and that the experiment has a high probability of achieving its accuracy goal of 0.5 milliarc sec/yr for both relativistic frame dragging and geodetic precession. Several members of the task group are worried that, despite heroic efforts, unspecified or unknown effects could seriously degrade the measurements made in orbit. This section concludes with some overall observations on the project.

SYSTEMS ENGINEERING

The systems engineering methodology used for the GP-B project appears to be excellent. Imposed and derived requirements for the hardware have been well defined and formally connected with relevant parts of the space vehicle. The requirements are currently

maintained with a rigorous procedure, and the task group has not identified any significant outstanding problems. Numerous elements of the space vehicle use flight-proven hardware, or low-risk modifications of it. For most remaining subsystems, the critical design criteria necessary to meet mission requirements have been validated by technology projects or by prototyping. The task group's overall assessment of the spacecraft status is that it presents no significant technical or schedule risks.

The probe and Dewar units incorporate new technologies and require new fabrication methods for dealing with extremely low temperatures and extraordinary magnetic shielding over large volumes. The fabrication, integration, verification, and acceptance testing of the payload will be one of the more challenging space-hardware projects attempted in the U.S. space program. Quantitative assessment of risks associated with this part of the GP-B project is therefore very difficult. Detailed verification of the whole flight system, including hardware, software, and internal and external environments, must be carried out. Moreover, the entire system must be controlled and monitored throughout its final acceptance, transportation, pre-flight checks, and boost into orbit. The discipline with which the GP-B team addresses these issues will be crucial to the project's overall chances of success.

HELIUM THRUSTERS

Technology for the new helium thrusters has been adequately demonstrated. However, system interactions and precise thrust control still need to be verified in dynamic integrated tests. A suitable test program should include a full range of simulations at the 3σ margins of "flying" the vehicle around the drag-free mass. Although the risks might appear to be low from

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a hardware standpoint, some of the margins available for deviations from expected behavior do not appear to be large, given the very small gap between the drag-free mass and its housing. The "safe mode" that uses magnetic torquers in place of the helium thrusters is a useful backup for attitude, roll, and pointing control, but not for drag-free flight around the proof mass. A careful risk assessment involving uncertainties in all crucial elements of this part of flight operations should receive close attention.

SAFETY MARGINS

Analysis of the safety margins for key system parameters shows that a few of them dominate the overall experimental errors. The available margins for most parameters are at least several times their 3σ values. Under such conditions the dominant risks arise from the design-validated configurations associated with each parameter, and not from technical limitations. As noted above, the experiment duration (which is determined by performance of the liquid helium storage system) has by far the greatest influence on final accuracy. For durations much less than a year, other parameters dominate because of averaging limitations. If the system operates near its ground-validated design characteristics, the design-goal accuracy of 0.5 milliarc sec/yr should be achieved some 5 to 6 months into the experiment. Successful operation for 13 months under design conditions for the most critical parameters, even allowing multiple standard deviations for the others, could provide a 60 percent margin beyond the design requirements.

Analysis of the experimental errors under expected orbital conditions shows that parameters affecting the spurious gyro drifts have very low sensitivities. For this reason, ground-based testing can directly validate these measurement-error profiles. Conditions of gyro-support damping in the ground tests, which

would influence the spurious drifts, appear to have low impact on the overall errors in orbit. Further analysis and updating of these sensitivities and margins should be carried out on a continuing basis as the validation programs proceed.

TECHNOLOGY TRANSFER

The task group is deeply impressed by the very careful thought, design, and testing invested in the cryogenic aspects of GP-B. The launch vehicle itself is an exceptionally interesting example of Dewar design. The container housing some 2000 liters of liquid helium for the 18- to 20-month mission contains many innovations. It is unusually efficient, despite the requirement that most of the helium be stored in the superfluid state. The low-conductivity shock absorbers used to stabilize the Dewar during launch are innovative and effective. The titanium alloy used in the narrow part of the container, near the top, is a new material that could improve many or even most liquid helium containers. The various glues, composite materials, and fasteners used in the design are unknown by much of the community of low-temperature experimentalists.

Designers of other cryogenic apparatus would profit from published reports of the materials used in the apparatus. A detailed discussion of thermal shielding used to optimize the cryogenic efficiency would be especially useful. The community of those who use non-magnetic structures in other SQUID experiments could save a great deal of time by knowing which materials the GP-B team has found to be free of magnetic contamination. The task group strongly urges that the technology developed during NASA's support of GP-B be reported soon in the open literature for the benefit of the entire scientific community.

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