DOCUMENT RESUME

ED 463 153 SE 065 783

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TITLE	Gravity Probe B: Examining Einstein's Spacetime with Gyroscopes. An Educator's Guide with Activities in Space Science.
INSTITUTION	National Aeronautics and Space Administration, Washington, DC.
PUB DATE	2002-03-00
NOTE	48p.
AVAILABLE FROM	Web site: http://einstein.stanford.edu/.
PUB TYPE	Guides - Classroom - Teacher (052)
EDRS PRICE	MF01/PC02 Plus Postage.
DESCRIPTORS	Higher Education; Middle Schools; *Physical Sciences; Relativity; *Science Activities; *Science Experiments; Science Instruction; Secondary Education; *Space Sciences
IDENTIFIERS	Telescopes

ABSTRACT

This teaching guide introduces a relativity gyroscope experiment aiming to test two unverified predictions of Albert Einstein's general theory of relativity. An introduction to the theory includes the following sections: (1) "Spacetime, Curved Spacetime, and Frame-Dragging"; (2) "'Seeing' Spacetime with Gyroscopes"; (3) "The Gravity Probe B Science Instrument"; and (4) "Concluding Questions of Gravity Probe B." The guide also presents seven classroom extension activities and demonstrations. These include: (1) "Playing Marbles with Newton's Gravity"; (2) "The Speed of Gravity?"; (3) "The Equivalence Principle"; (4) "Spacetime Models"; (5) "Frame-Dragging of Local Spacetime"; (6) "The Miniscule Angels"; and (7) "Brief History of Gyroscopes." (YDS)

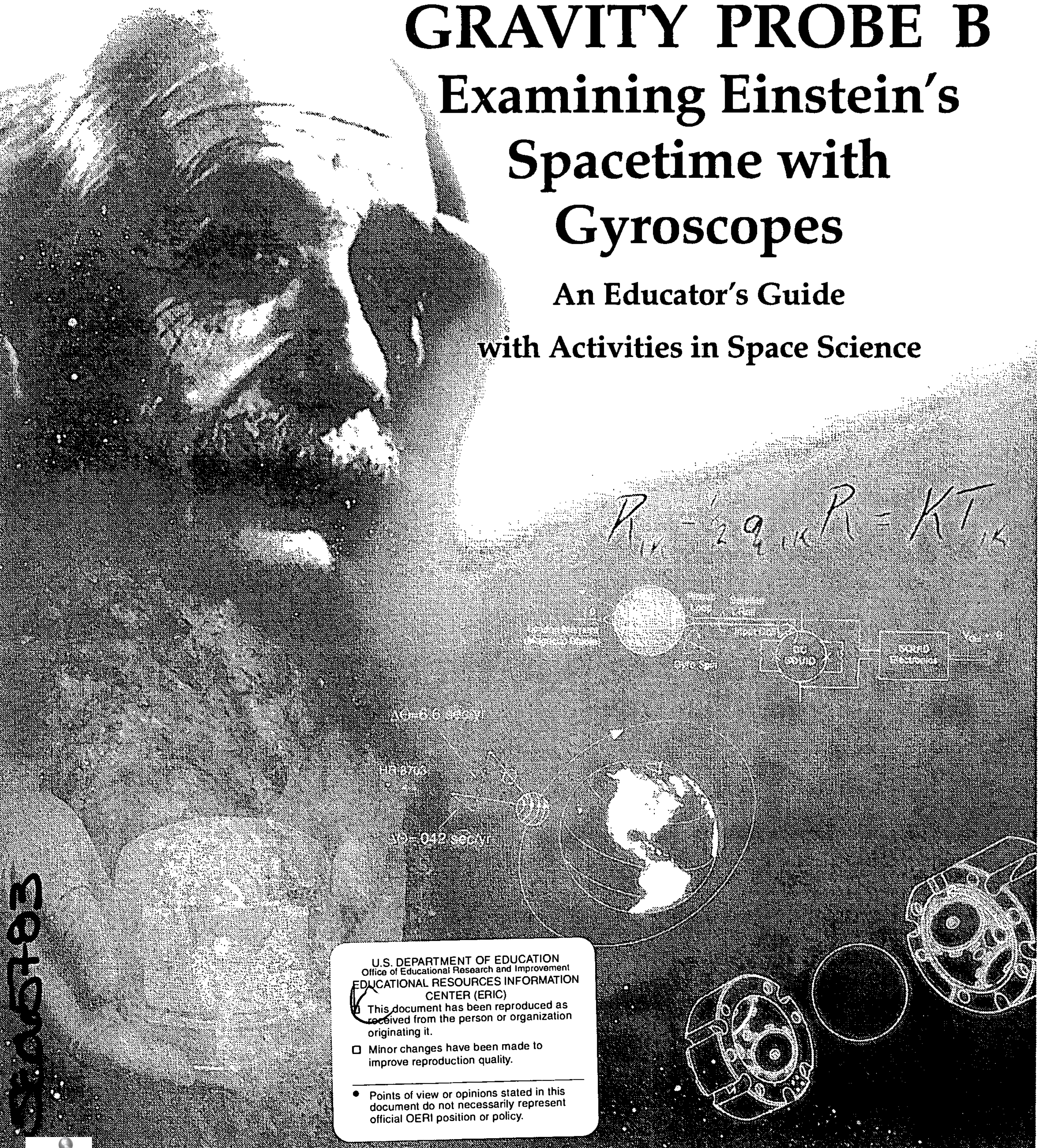
National Aeronautics and
Space Administration

Educational Product	
Educators & Students	Grades 7-College

GRAVITY PROBE B

Examining Einstein's Spacetime with Gyroscopes

An Educator's Guide with Activities in Space Science



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Educator's Guide created in March 2002
by Shannon K'doah Range and Jennifer Mullins.

THIS EDUCATOR'S GUIDE ADDRESSES THE FOLLOWING NATIONAL SCIENCE EDUCATION STANDARDS:

CONTENT STANDARD A
* Understandings about scientific inquiry

CONTENT STANDARD B
* Structure of atoms
* Motions and forces
* Conservation of energy and increase in disorder
* Interactions of energy and matter

CONTENT STANDARD D
* Origin and evolution of the universe

CONTENT STANDARD E
* Abilities of technological design
* Understandings about science and technology

CONTENT STANDARD G
* Science as a human endeavor
* Nature of scientific knowledge
* Historical perspectives

GRAVITY PROBE B
Examining Einstein's Spacetime with Gyroscopes

An Educator's Guide

with Activities in Space Science

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An Introduction To Gravity Probe B

Examining the Fundamental Structure of the Universe

Gravity Probe B is a **relativity gyroscope experiment** developed by NASA's Marshall Space Flight Center, Stanford University, and Lockheed Martin to test **two extraordinary, unverified predictions** of Albert Einstein's general theory of relativity (1916).

1) **The curved spacetime, or geodetic, effect** - Einstein's theory predicted that the presence of a mass in space, such as the Earth, **would warp local spacetime, creating a dip or curve in spacetime.**

2) **The frame-dragging effect** - A few years after Einstein published his theory, physicists Lense and Thirring predicted that **the rotation of a mass in space would twist or drag the local spacetime frame around it.**

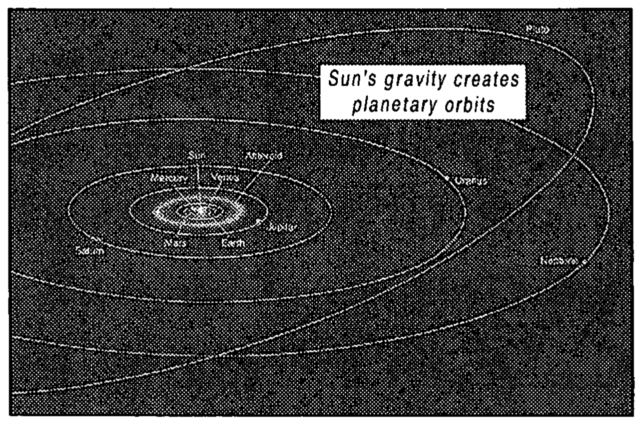
To observe and measure these effects, Gravity Probe B will **launch four sophisticated gyroscopes into low-Earth polar orbit (400 miles) for eighteen to twenty-four months.** Once in orbit, each gyroscope' spin axis will be monitored as it travels through local spacetime. Scientists have predicted that each gyroscope's spin axis will turn 6.6 arcseconds due to the local spacetime curvature, and 42 milliarcseconds due to the frame-dragging effect.

Spacetime, Curved Spacetime, and "Frame-Dragging"

In Einstein's theory of general relativity, space is transformed from the Newtonian idea of a vast emptiness, with nothing but the force of gravity to rule the motion of matter through the universe, to an invisible fabric of spacetime, which "grips" matter and directs its course.

A. Two Observations, One Revolution (From Gravity to Spacetime)

Newton's theory of gravity (1687) is as familiar to us as walking down a hill. As we put one foot in front of the other, the invisible force of gravity reaches out from the Earth and pulls each foot down to the ground. We feel the pull of the force and let our foot fall to the ground and we continue down the hill on our merry way. The same invisible force that keeps us Earth-bound keeps the planets in orbit around the Sun. The Sun's gravity reaches out across empty space and constantly pulls the planets toward it, preventing them from zooming out of our solar system.



This theory remained the strongest explanation for the planetary orbits and the apparent "falling" motion of objects on Earth for several centuries. It was not until the early 20th century when Einstein began working on his theories of relativity that Newton's theory of gravity was seriously challenged.

In 1905 and 1906 Einstein laid out his theory of special relativity in a collection of papers. Central to this theory was his claim that the speed of light in a vacuum (~300,000 km/sec) was the speed limit of all matter and energy in the universe. While matter and energy could travel at speeds approaching or equaling the speed of light, they could never surpass it.

With this principle in hand, Einstein turned his attention to Newton's theory of gravity. Einstein focused on two observations that challenged Newton's theory. The first related to the speed limit of light, and its implications for the speed limit of the force of gravity. The second related to the Equivalence Principle.

SPECIAL vs. GENERAL

Special relativity (1905) refers to the laws of physics in a special situation - when a frame of reference is ***in uniform motion***.

General relativity (1916) describes the laws of physics in all situations in general, whether the frame of reference is ***in uniform motion or is accelerating near a gravitational field***.

Observation #1 - Instant Propagation Problem

Newton stated that the attractive force of gravity emanated from all matter, but he did not explain how it physically transmitted from one mass to another, nor how long this transmission took to occur. He simply inferred that the force of gravity traveled instantly across empty space, propogating from one mass to another.

> **NO HYPOTHESIS**
>
> In the `Principia' (1687), Newton states that "there is a power of gravity pertaining to all bodies, proportional to the several quantities of matter which they contain." As the story goes, when Newton was questioned about how this "power of gravity" transmitted from one body to another, he responded, "I make no hypothesis."

For Einstein, this assumption could not be possible. The speed of light was the speed limit of the universe for all matter, energy, and forces, including Newton's gravity. Einstein knew that light traveled remarkably fast, but it did not travel instantly across the solar system or the universe. In fact, light took many minutes and even hours to travel from the Sun to the planets. Therefore, the force of gravity could not be transmitting instantly from the Sun to the planets - it must take as many minutes to cross the distance as it took light to do so.

Could special relativity be wrong? Or did Newton's theory of gravity need a revision? This is the instant propogation problem.

Observation #2 - The Equivalence Principle

The Equivalence Principle was nothing new in physics when Einstein came along. It was understood in a simple form by Galileo and as far back as the Greek thinkers. Simply stated, this principle asserts that all physical experiments operate identically whether operating in a free-falling frame of reference (e.g., a free-falling elevator) or in a free-floating frame of reference virtually unaffected by gravity (e.g., an orbiting spacecraft). In both situations, the experimenter would feel weightless - the frames of reference are equivalent.

GRAVITY is ACCELERATION

EINSTEIN'S "HAPPIEST THOUGHT"

"For an observer falling freely from the roof of a house, there exists - at least in his immediate surroundings - no gravitational field. Indeed, if the observer drops some [masses], then these remain to him in a state of rest, or uniform motion....

The observer, therefore, has the right to interpret his state as 'at rest' [even though he appears to be falling to the rest of us]."

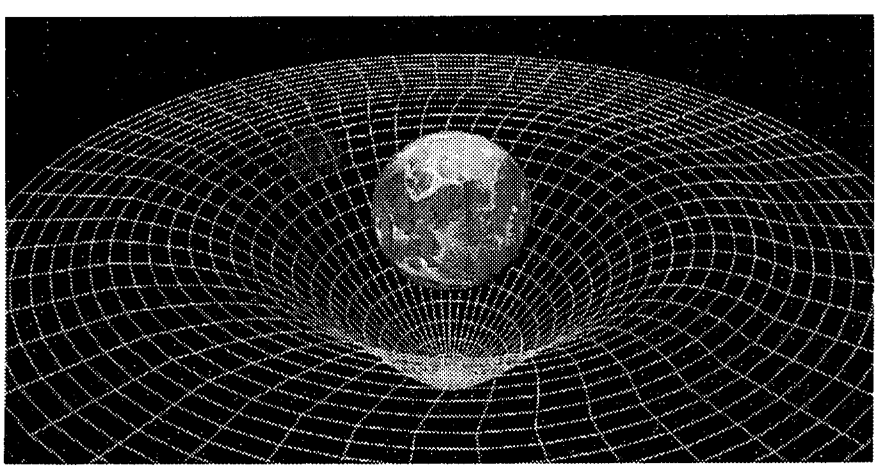
A corollary to this equivalent weightlessness is the equivalence of physics on the Earth's surface and physics in an accelerating spaceship. On Earth, the experimenter feels the pull of gravity down. All objects resist being lifted, and when released, fall to the ground at 9.8 m/s^2. In a spaceship accelerating upward at 9.8 m/s^2, the physics are identical. The experimenter feels a pull toward the floor of the spaceship. All objects resist being lifted from the floor of the spaceship and, when released, fall at 9.8 m/s^2. Gravity creates the pull on Earth; acceleration creates the pull in the spaceship. The force of gravity and the force of acceleration are virtually indistinguishable.

If the effects of gravity's pull were identical to the effects of acceleration, was gravity really an independent force? Wasn't gravity just acceleration?

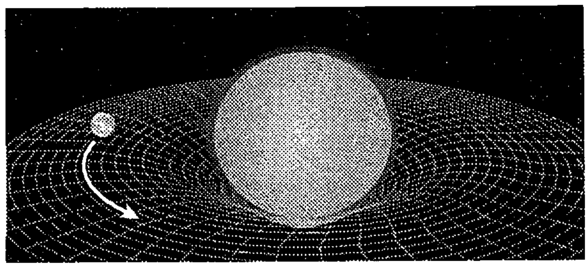
B. A New Understanding: Curved Spacetime

In 1916, Einstein addressed these two contradictions (the instant propogation problem and the equivalence of gravity and acceleration) by reconstructing the theory of gravity. Einstein presented the world with a new understanding of the world - his theory of general relativity. In this theory, space is not an empty void, but an invisible structure called spacetime. Nor is space simply a three-dimensional grid through which matter and energy moves. It is a four-dimensional structure whose shape is determined by the presence of matter and energy.

Around any mass (or energy), spacetime is curved. The presence of planets, stars and galaxies deform the fabric of spacetime like a large ball deforms a bedsheet. (This deformation occurs in four dimensions, so the two-dimensional bedsheet is a limited model. Try visualizing these depressions on all sides of a planet to build a more accurate image of this concept.)

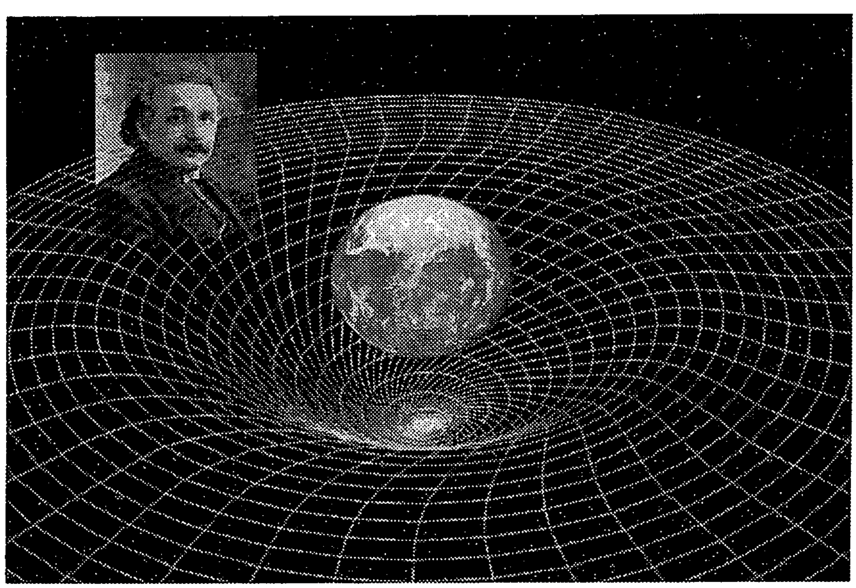


When a smaller mass passes near a larger mass, it curves toward the larger mass because spacetime itself is curved toward the larger mass. The smaller mass is not "attracted" to the larger mass by any force. The smaller mass simply follows the structure of curved spacetime near the larger mass. For example, the massive Sun curves spacetime around it, a curvature that reaches out to the edges of the solar system and beyond. The planets orbiting the Sun are not being pulled by the Sun; they are following the curved spacetime deformed by the Sun.



C. The Second Implication: Frame-Dragging

A few years after Einstein submitted his theory of curved spacetime, Austrian physicists Joseph Lense and Hans Thirring predicted that a mass could deform spacetime in a second way - through frame-dragging (1919). They proposed that the rotation of planets and stars (i.e., any rotating mass) twists the structure of spacetime near that mass. Not only is local spacetime curved near the Sun, it is twisted by the the Sun's rotation. Lense and Thirring predicted that this effect would be extremely small, and become smaller farther from the rotating mass, but it would occur around every rotating planet, star, galaxy, or person.



D. Einstein May Be Right, But Newton Is Not Wrong

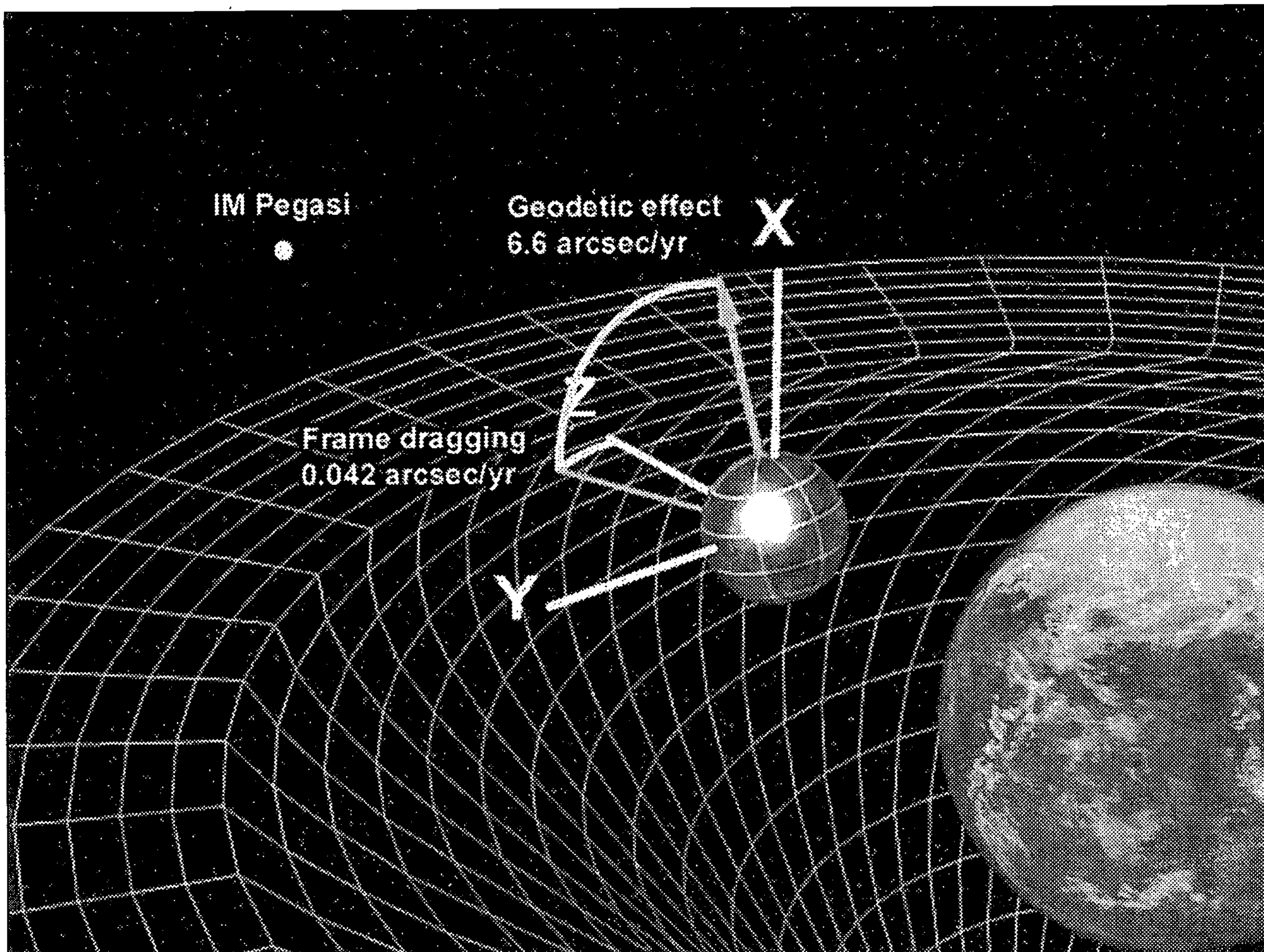
From this description of the contradictions found in Newton's theory of gravity and Einstein's resolution of them, one may get the impression that Einstein's theory of general relativity completely replaces Newton's theory of gravity. Now that we are in possession of Einstein's concept of spacetime, we should toss "the force of gravity" out of our physics conversations.

This is not the case. We need to retain both Einstein's theory of curved spacetime and Newton's theory of gravity in our understanding of our universe. Einstein's theory does provide us with a more accurate understanding of the underlying structure of the universe. However, unless one observes phenomena moving near the speed of light (e.g., starlight, radio waves, quasar jets) or near enormous masses (e.g., neutron stars, galaxies, black holes), the actual effects of curved spacetime and frame-dragging are barely distinguishable from those predicted by the theory of gravity. In our common physical experience on Earth, where the fastest phenomena rarely reach 0.0001% of *c*, Newton's theory of gravity suffices. Its mathematics are much, much simpler than the mathematics of motion in curved spacetime, and it provides a functional picture of our physical world.

"SPACE" or "SPACETIME"

What is the difference between "space" and "spacetime"? In "space", measurements of length and time are fixed. In "spacetime", length and time are relative, dependent on your speed and location in space. Length contracts and time stretches.

"Seeing" Spacetime with Gyroscopes



GRAVITY PROBE B FAST FACTS

A nearly-perfectly spherical gyroscope orbits in spacetime 400 miles above the Earth. At the beginning of the mission, the gyroscope's spin axis points at IM Pegasi, a distant star (along the Z-axis). After one year, theoretical calculations predict that the gyroscope's spin axis will turn in two directions: 42 milliarcseconds horizontally (towards the Y-axis) due to frame-dragging, and 6.6 arcseconds vertically (towards the X-axis) due to its orbit through local curved spacetime, called the "geodetic effect".

Duration....................18-24 months
Orbital altitude.........400 miles
Gyroscope..................1.5-inch sphere
Margin of error.......< 0.5 milliarcsecond
Telescope....................5.5-inch aperture, 14-inch length
Dewar.........................608-gallon capacity, 9-foot height

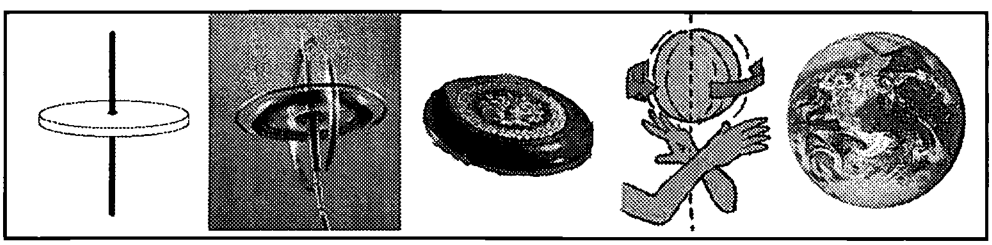
A. The Concept of Gravity Probe B

According to Einstein's theory of general relativity (1916), all planets and stars reside in an invisible, intangible structure of spacetime. The Earth, like all mass-energy, affects local spacetime in two ways. Earth's presence warps or curves spacetime around it, and Earth's rotation drags or twists the local spacetime frame with it (called "frame-dragging").

How could one test Einstein's theory? How could one "see" this invisible structure and measure the shape and motion of this intangible spacetime?

In 1960, Stanford University physicist Leonard Schiff and his colleagues were discussing the possible scientific benefits of creating a perfectly spherical gyroscope. Certainly this perfect gyroscope could improve navigation of planes, rockets and satellites. But Schiff proposed something else - a way to "see" local spacetime.

Schiff suggested that if they placed a near-perfect spinning gyroscope in spacetime above the Earth and monitored the direction its axis pointed, the floating gyroscope could show them the shape and behavior of our invisible spacetime frame. The experiment would only work with a near-perfect gyroscope, as the effects of spacetime's curvature and motion were predicted to be microscopicly small.



Why a gyroscope? Gyroscopes, or any spinning object, remain oriented in the same direction as long as they are spinning, a property called rotational inertia. A common example of this inertia is a spinning top. It balances on its end while spinning, yet topples over when friction slows it down. While it spins, its rotational inertia keeps it pointed straight up, oriented in its original direction.

ROTATIONAL INERTIA

The resistance that a mass exhibits to having its speed of rotation altered by the application of a torque (turning force); any spinning mass will continue to rotate as long as no outside force acts upon it.

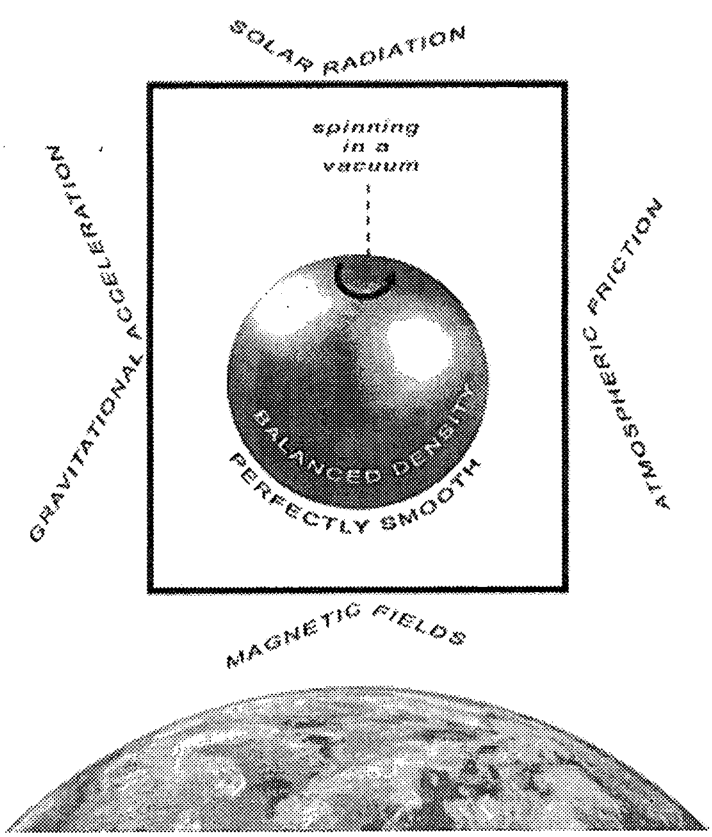
Accordingly, if the top was spinning in the near-vacuum of space, it would remain constantly oriented in its original direction, since there would be no forces to slow it down. Our Earth is a prime example of this. The Earth's axis is oriented 23.5 degrees from vertical, relative to the Sun. It has remained in this position due in part to its rotational inertia.

If a perfectly-spherical, spinning gyroscope floated above the Earth in spacetime, and it was protected from any external forces that could re-orient it (*e.g., gravity, radiation, atmosphere, magnetic fields, electrical charges*), and any internal imbalances were removed (*e.g., imperfect shape, unbalanced density, surface imperfections*) it would remain pointing in its original direction. The only thing that could alter its orientation would be the structure of spacetime itself.

EARTH'S PRECESSION

Like all spinning tops or gyroscopes, the Earth's axis does move slightly while it spins - a motion called "precession". Every 26,000 years, the Earth's axis "precesses" in a complete circle, 23.5 degrees from vertical. While the Earth's current "North Star" is Polaris, in 13, 000 years it will be Vega. Then 13,000 years later, Polaris again will be our North Star.

Compared to the Earth, Gravity Probe B's gyroscope cannot "precess" hardly at all. For this experiment to work, it must stay within two ten-millionths of a degree of vertical (<0.00000014° of precession)!



If the local spacetime in which the gyroscope was floating was curved or was twisting, the gyroscope's position would change to follow this curve or twist. If we could monitor this change in orientation, we could "see" the shape and behavior of spacetime itself! This is the mission of Gravity Probe B - to "see" our local spacetime, and measure it more precisely than any experiment in history.

THREE TESTS OF RELATIVITY

When Einstein published his theory of general relativity in 1916, it was just that - a theory. Since then scientists have been attempting to design empirical tests of his theory to either confirm or disprove it. Gravity Probe B is the most sophisticated effort in this line of experiments.

Einstein suggested three ways that general relativity could be empirically verified: 1) measure starlight deflection, 2) recalculate the Mercury perihelion question, and 3) measure the red-shift of light. Each of these tests have been performed at higher and higher levels of precision over the past century, each time supporting Einstein's theory. However, compared to other broad theories including electromagnetism and nuclear theory, scientists have barely scratched general relativity's surface.

B. The Mechanics of Gravity Probe B

The Gravity Probe B mission plan is as follows:

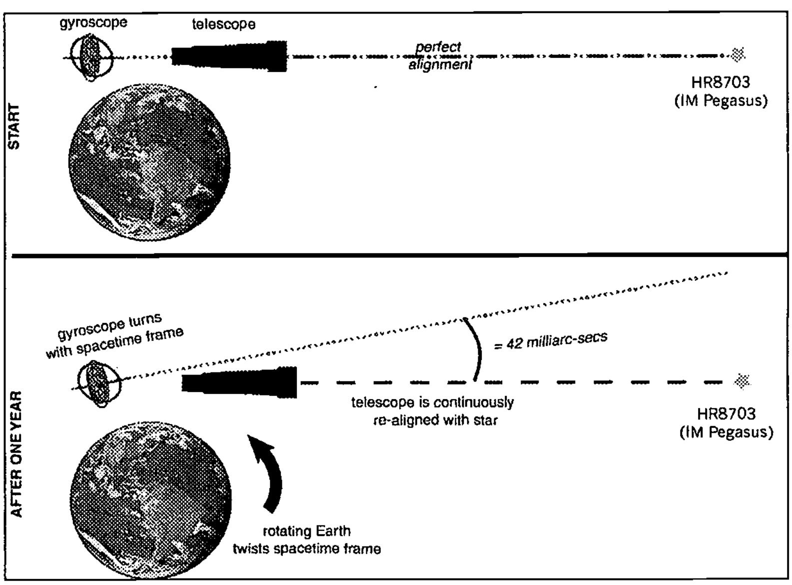
1. Place a satellite into polar orbit. Inside the satellite are the gyroscopes (GP-B uses four gyroscopes for redundancy) and a telescope.

2. Point the telescope at a distant star (called the "guide star"). GP-B aligns the telescope by turning the satellite because the telescope is fixed within the satellite.

3. Align the gyroscopes with the telescope so that when they are spinning, each spin axis also points directly at the guide star.

4. Spin up the gyroscopes and remove any external forces (pressure, heat, magnetic field, gravity, electrical charges) so the gyroscopes will spin unhindered, in a vacuum within the satellite, free from any influence from the satellite itself.

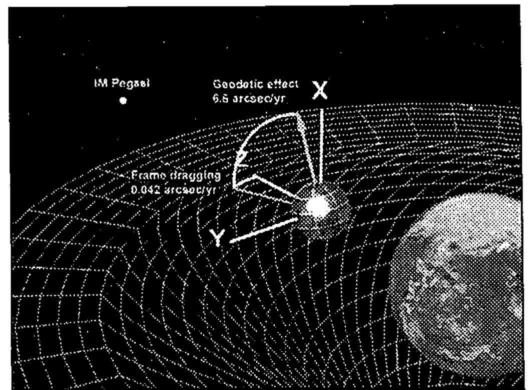
5. Monitor the orientation of the gyroscopes over 1-2 years. Keep the telescope (and the satellite) fixed on the guide star and measure any angles that open up between the telescope's orientation and each gyroscope's spin axis. If local spacetime around the Earth is curved and frame-dragging occurs, the gyroscopes should slowly turn during this time, revealing its shape and motion.



According to Schiff's calculations, with the gyroscopes and satellite orbiting 400 miles (640 km) above the Earth's surface, the orientation of each gyroscope's spin axis should shift **6.6 arcseconds/year due to the local spacetime curvature** and should turn **42 milliarcseconds/year due to the frame-dragging** effect. In other words, Gravity Probe B intends to use gyroscopes and a telescope orbiting above Earth to measure two microscopic angles, each predicted to be a tiny margin of a single degree.

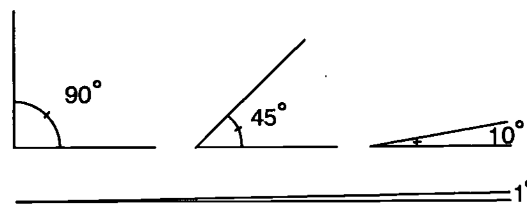
C. Two Microscopic Angles: How Small is Small?

The central challenge of the Gravity Probe B mission is to build a gyroscope, telescope and satellite that can precisely measure two miniscule angles. Because these angles are so small, GP-B has very little margin of error. The telescope must point to within one milliarcsecond of the exact center of the guide star. GP-B must know the gyroscope's orientation to within one-half of a milliarcsecond (0.5 milliarcseconds)!



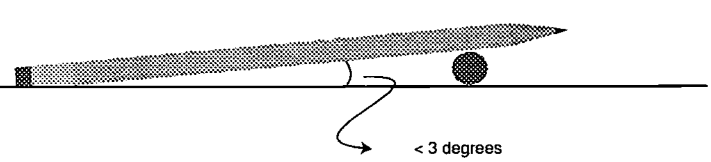
"Curvature angle" = 6.6 arcseconds
"Frame-dragging angle" = 42 milliarcseconds

These angles are almost too small to comprehend. We know that street corners make 90 degree angles, and the diagonal of a square is 45 degrees. A ramp into a building or up to the curb is usually between five and ten degrees. Walking on a slope of one or two degrees seems like practically nothing - it feels like walking on flat ground.



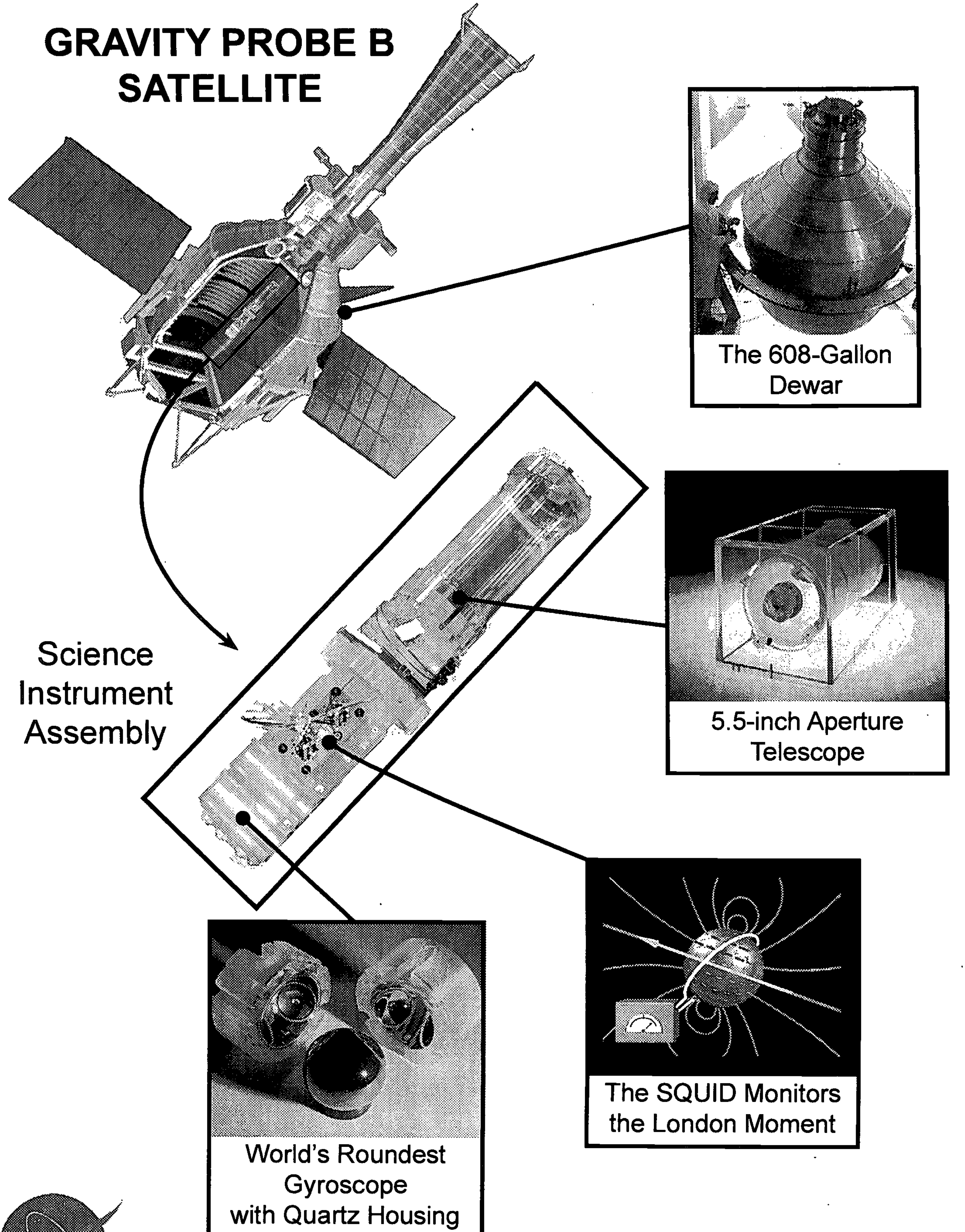
However, a slope (or angle) of one degree is like climbing Mount Everest compared to the angles GP-B is trying to measure. The "curvature angle", 6.6 arcseconds, rises less than two-thousandths of one degree. And the "frame-dragging angle", which is 42 milliarcseconds, is over 150 times smaller than that, rising a mere 0.000012 degrees (1.2 hundred-thousandths of a degree). If you "climbed" a slope of 42 milliarcseconds for 100 miles, you would be only *one inch higher* than you were when you started out!

One way to see how small these angles are is to lay a pencil across another pencil. Look at the angle between the leaning pencil and the table top. This angle is fairly small - about three degrees. To imagine how small 42 milliarcseconds is, break this angle into about 250,000 equal pieces! GP-B must measure this angle within a precision of 0.5 milliarcseconds - an angle 20,000,000 times smaller than the angle between the pencil and the table top!

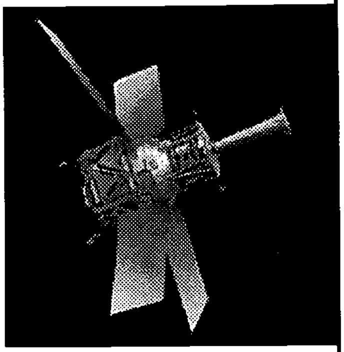


See Classroom Extensions for r

GRAVITY PROBE B SATELLITE

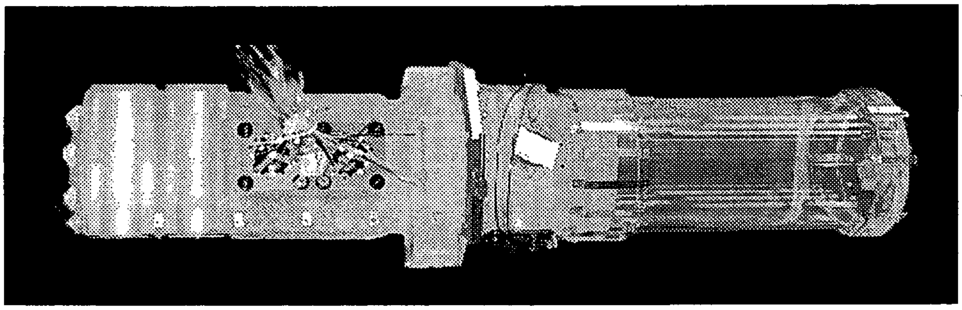


The Gravity Probe B Science Instrument

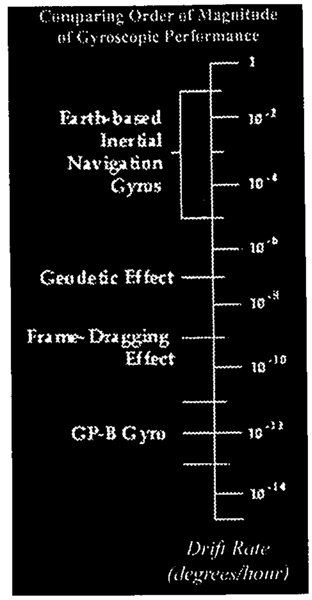


To test Einstein's theory of general relativity, Gravity Probe B must measure two miniscule angles with a spinning gyroscope floating in space. While the concept of Gravity Probe B is relatively simple in design, the technology required to build it is some of the most sophisticated in the world. Scientists from Stanford University, NASA's Marshall Space Flight Center, and Lockheed Martin Corporation have drawn from a diverse array of physical sciences, and have invented much of the technology that makes the mission possible. In fact, much of the technology did not even exist when Leonard Schiff conceived of the experiment in the early 1960's.

The Gravity Probe B science instrument takes the shape of a long rectangular block with four gyroscopes lined up behind a telescope that peers out the top of the Gravity Probe B satellite. Each gyroscope is suspended in a quartz housing, surrounded by a metal loop connected to a SQUID to monitor its orientation. The fused quartz gyroscopes sit in a fused quartz block that is bonded to the fused quartz telescope. These three components make up the Science Instrument Assembly (SIA).



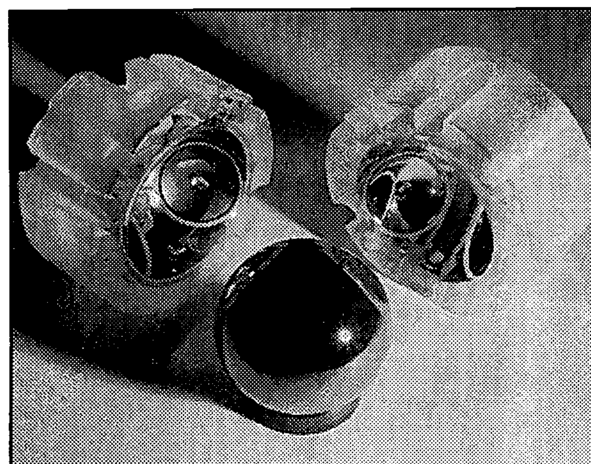
A. The World's Most Perfect Gyroscope



To measure the microscopic angles that Leonard Schiff predicted (6.6 arcseconds and 42 milliarcseconds), Gravity Probe B needed to build a near-perfect gyroscope - one that would not drift (or wobble) more than one hundred-billionth of a degree from vertical each hour that it was spinning. This is an especially stiff challenge, given that all gyroscopes tend to wobble slightly while they are spinning. Even the most sophisticated Earth-based gyroscopes, found in missiles and jet airplanes, wobble seven orders of magnitude more than GP-B could allow.

What creates the wobble in even the best gyroscopes? Three physical characteristics of a gyroscope can cause its spin axis to drift - 1) an imbalance in mass or density distribution inside the gyroscope, or 2) an uneven, asymmetrical surface on the outside of the gyroscope causing air friction, or 3) friction between the bearings and axle of the gyroscope. This means it has to be perfectly balanced and homogenous inside, cannot have any rough surfaces outside, and must be free from any bearings or supports.

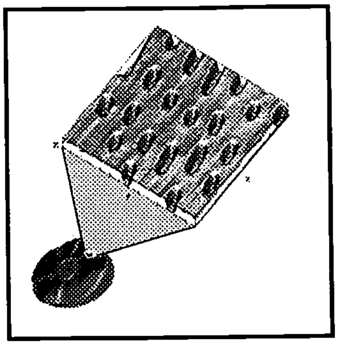
After years of work and the invention of numerous new technologies, this is the resul: a homogenous 1.5-inch sphere of pure fused quartz, polished to within a few atomic layers of perfectly smooth. It is the most spherical object ever made, topped in sphericity only by neutron stars!



Gravity Probe B gyroscope (rotor) with quartz housing halves. Each milky-colored quartz rotor is coated with a sliver-thin layer of niobium, a superconducting metal. Inside each housing, six electrodes electrically suspend the gyroscope allowing it to spin freely at 10,000 rpm. Channels are cut in the quartz housing to allow helium gas to start the rotor spinning. A wire loop embedded in the housing acts as a SQUID to detect any change in direction of the gyroscope's axis.

Inside, the gyroscope is solid fused quartz. It was carved out of a pure quartz block grown and baked in a lab. Its interior parts are all identical to within two parts in a million (that's like having 999,998 identical siblings out of 1,000,000!)

On its surface, the gyroscope is less than 3 ten-millionths of an inch from perfect sphericity. This means that every point on the surface of the gyroscope is the exact same distance from the center of the gyroscope to within 0.0000003 inches.

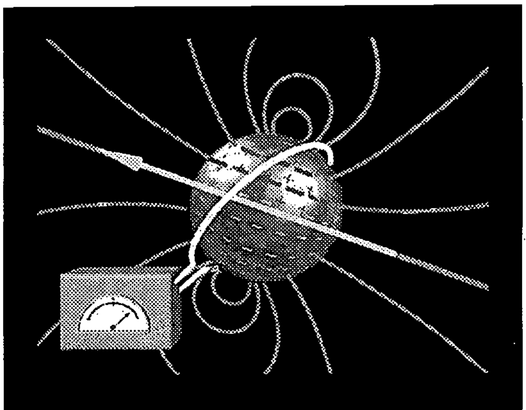


Here are two ways to imagine how smooth this is. First, compare the GP-B gyroscope's smoothness with another smooth object - a compact disk. CD's and DVD's both appear and feel incredibly smooth. The pits on the compact disk's surface, which carry the digital information, are less than one micrometer (one millionth of a meter) deep. However, compared to the GP-B gyroscope, the surface of a CD is like sandpaper! The bumps and valleys on the surface of the GP-B gyroscope are less than 1/100th of a micrometer (< 10 billionths of a meter). Viewed at the same magnification, one could barely see any imperfections on the gyroscope's surface!

Second, imagine the GP-B gyroscope is enlarged to the size of the Earth's moon, making the gyroscope more than 90 million times larger than its actual size. Any imperfections on the surface of the gyroscope would be more than 90 million times larger as well. Even at this size, however, with every bump and dip enlarged more than 90 million times, the distance between its high point and low point on the surface would be little more than *two feet*! From Earth, the "gyroscope moon' would look like a perfect craterless orb in the sky.

B. The London Moment and SQUID: Reading the Unreadable

The Gravity Probe B gyroscope is nearly perfectly spherical and nearly perfectly homogenous. While this ensures that the gyroscope will spin with near-perfect stability, its "near-perfect-ness" creates a daunting challenge. Since the gyroscope's surface cannot be marked in any way (this would disrupt its smoothness and sphericity, and disturb its rotation), GP-B scientists cannot see exactly which direction its spin axis is pointing. For GP-B to measure the movement of the gyroscope, and "see" the shape and motion of local spacetime, the scientists must be able to monitor the spin axis orientation to within 0.5 milliarcseconds.

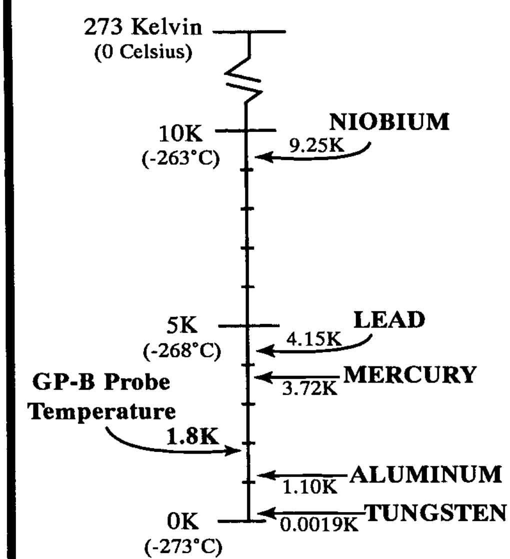


The Gravity Probe B gyroscopes are each coated with niobium, a superconducting metal. When rotating, the niobium layer generates a magnetic field which aligns exactly with the gyroscope's spin axis. A SQUID monitors the magnetic field's orientation with a metal loop surrounding the gyroscope, which tells the GP-B scientists exactly which direction the gyroscope is pointing to within 0.5 milliarcseconds.

How can one monitor the spin axis orientation of this near-perfect gyroscope without knowing where the spin axis is on the gyroscope? What tool could sense its orientation without disturbing its rotation? The answer comes from a unique quantum-mechanical phenomenon called the "London moment".

Fritz London, a physical scientist, was experimenting in the early 1900's with metals with a unique property called "superconductivity". This is a property of only some metals and alloys in which the metal (or alloy) conducts electricity without any resistance. When electricity flows through metals, such as copper wires, at room temperature, there is always some resistance to the electrons flowing through the metal. Yet, some metals can conduct electricity without any resistance, and are called "superconducting metals." Pure metals must be dramatically cooled, reducing their temperature to just a few degrees above absolute zero (0 Kelvin, -273°C, -549°F), for this property to emerge, while certain alloys become superconductive at moderately cool temperatures.

Ultra-Low Temperatures for Superconductivity

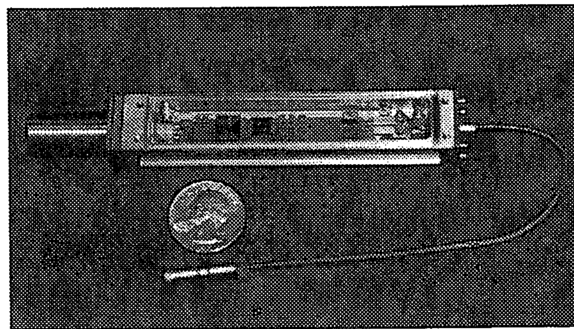


London discovered something remarkable about these superconducting metals; he discovered that when a superconducting metal sphere spins (or an object coated with a superconducting metal spins), it creates a magnetic field around itself.

On the surface of the spinning metal, electrons lag behind the metal's positively-charged atoms creating a small difference field. This difference generates a magnetic field. What is even more remarkable about this phenomenon (and fortunate for Gravity Probe B) is that the axis of this magnetic field *lines up exactly* with the axis of the spinning metal.

Here was the "marker" Gravity Probe B needed. GP-B scientists coated each quartz gyroscope with a sliver-thin layer of a superconducting metal, called niobium (1270 nanometers thick). When each niobium-coated gyroscope rotates, a small magnetic field surrounds each gyroscope. As Fritz London discovered, the axis of each magnetic field aligned itself perfectly with the spin axis of each spinning gyroscope. By monitoring the axis of the magnetic field, Gravity Probe B knows precisely which direction the gyroscope's spin axis is pointing.

The magnetic field axis is monitored with a special device called a SQUID (Superconducting QUantum Interference Device). The SQUID, about the size of stick of gum, is outside the gyroscope housing and is connected to a superconducting loop embedded within the quartz housing. When the gyroscope tilts, the London moment magnetic field tilts with it, passing through the superconducting loop. The SQUID detects this change in magnetic field orientation. The SQUID is so sensitive that a field change of 5 x 10^{-14} gauss (1/10,000,000,000,000 of the Earth's magnetic field), corresponding to a gyro tilt of 0.1 milliarcsecond, is detectable within a few days.



The Superconducting Quantum Interference Device (SQUID) is the size of a stick of gum.

Using the London moment to monitor the gyroscope's orientation is the one readout scheme perfect for Gravity Probe B: extremely sensitive, extremely stable, applicable to a perfect sphere, and - most importantly - exerts no significant reaction force on the gyroscope.

C. The Telescope: Following The Guide Star

During this mission, GP-B predicts that the spin axis of each gyroscope will move with the curvature and twist of local spacetime. The only way we can see this motion is by comparing each spin axis to a fixed line of reference. In this mission, the fixed reference line is the line between the telescope and our guide star, IM Pegasus. The telescope must remain fixed on the exact center of the guide star (within one milliarcsecond, or 1 millionth of an inch) throughout the mission or GP-B will lose its single critical reference line.

IM PEGASUS FACTS

Distance - ~300 light years

Right Ascension - 22.50'34.4"	Magnitude max. - 5.85
Declination - 16.34'32"	Magnitude min. - 5.6

Focusing on the exact center of a star would not be so hard if stars were fixed points of sharp light as they appear to be to the naked eye. However, IM Pegasus, like most stars, wanders across our sky, following a spiraling pattern instead of a linear path, and its light diffracts, or spreads out, as it travels across the universe to our telescope.

The Wandering Star

The wandering motion of the star around the sky is monitored by a sophisticated system of radio telescopes operating in conjunction with each other, called the Very Long Base Interferometer (VLBI). Telescopes from New Mexico to Australia to Germany focus on our guide star and map its movements as if one telescope dish the size of the Earth was focused on the star. The motions of the guide star are compared to a distant quasar. Quasars are extremely large masses that reside at the edge of the universe, far beyond the guide star. Because of their distance and size, they appear exceptionally still relative to the other stars in the sky, and provide a valuable reference point for GP-B to track the wandering guide star.

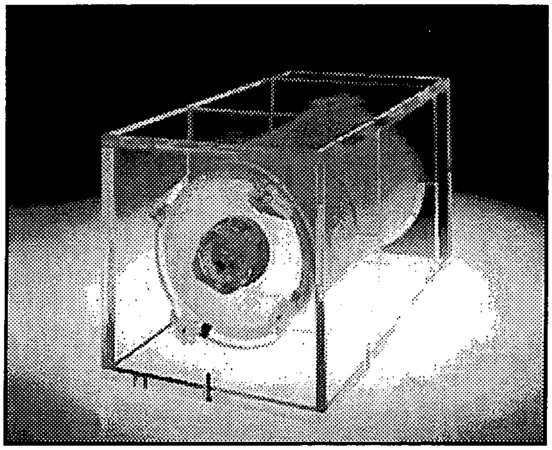
Diffracted Starlight

Diffraction occurs when the photons in a light ray spread out while travelling across space. The light from IM Pegasus spreads out to a diameter of 1,400 milliarcseconds, corresponding to an image 0.001 inch across. GP-B must find the exact center of the guide star to within one milliarcsecond, or 0.000001 inches. GP-B scientists resolve this issue in two ways: build an incredibly stable telescope that is free from the smallest amount of gravitational sag, and send the starlight through a super-sensitive palm-sized Image Divider Assembly (IDA) within the telescope.

The telescope itself is a 14-inch block of pure fused quartz, identical to the pure fused quartz used for the gyroscopes. Its mirrors are exquisitely polished and its components are connected through a process called "molecular adhesion". In this process, the surface of each component is polished so smoothly that the molecules of each surface "attach" to each other using the same electrical attraction that occurs on a molecular level.

PEGASUS or PEGASI?

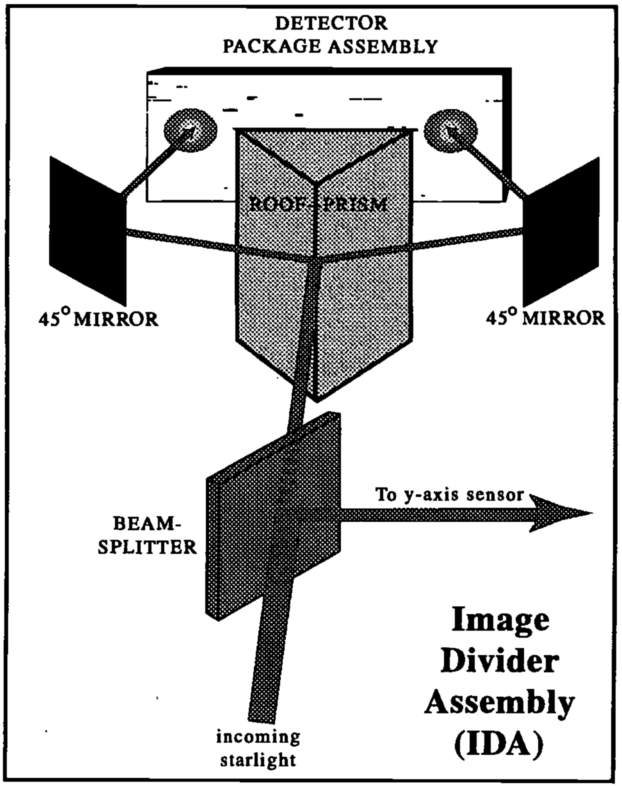
The guide star for GP-B is often referred to as "IM Pegasus". However, GP-B's guide star is actually a ***binary star system***, like 46% of the stars in our universe. The binary star system consists of two stars closely orbiting each other. The stars are in such tight orbits around each other that they appear to us as one dot of light. We can only distinguish each individual star in the binary system with a powerful telescope. So should we call it "Pegasus" or "Pegasi" (the plural)? Either one works - just remember that nearly half of the individual dots of starlight in the sky are really a dancing pair.



Most telescopes are capable of finding the exact center of a star by focusing the starlight on a single sensor. The sensor reads how much light is hitting each half of it. The telescope's alignment is adjusted until each half of the sensor is receiving exactly half of the incoming starlight.

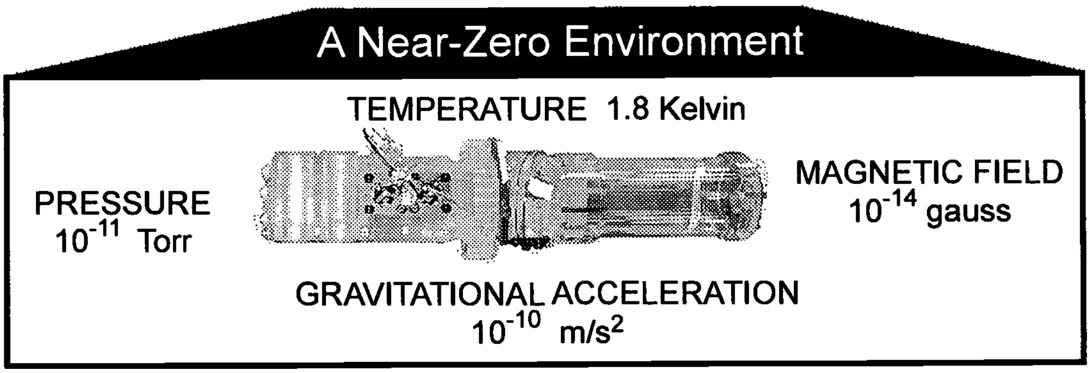
Unfortunately, this method is not precise enough for GP-B. No single sensor is small enough or sensitive enough to split the tiny amount of starlight with which GP-B is working, and aim the telescope within one milliarcsecond. So GP-B created an Image Divider Assembly (IDA), placed on the end of the telescope. The starlight enters the IDA after being focused by three mirrors in the quartz block telescope. The beam is first divided by a beam-splitter, deflecting one half of the starlight, and allowing the other half to continue straight through. The deflected beam aligns the telescope along the y-axis. The continuing beam aligns the telescope along the x-axis.

Each beam then hits a roof-prism (a prism with a peaked edge pointed toward the light), which slices the image in two. Each part of the sliced image is directed toward its own sensor on the Detector Package Assembly (smaller than a dime) and the electrical readouts are compared. When the telescope is pointed exactly at the center of the star (to within one milliarcsecond), the electrical flux (amount of signal) from each sensor will be identical. If they are not identical, the satellite turns the telescope to adjust its aim so when the starlight strikes the roof-prism, exactly half of the beam will hit each sensor.



D. The Force-Free Environment

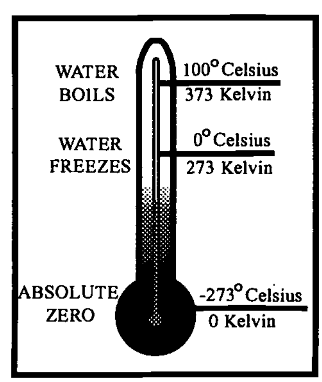
The Gravity Probe B science instrument (four gyroscopes in housings, sitting in a fused quartz block molded to the fused quartz telescope) is designed to make incredibly-precise measurements of the shape and behavior of local spacetime around Earth. However, this instrument will operate properly only if protected from any external forces. The slightest amount of heat or pressure, the influence of a magnetic field, any kind of gravitational acceleration, or the tiniest amount of atmospheric turbulence will destroy the accuracy of the instrument. For Gravity Probe B to succeed, the instrument must be placed in a near-zero environment.



1. Near-Zero Temperature: Near Absolute Zero

Gravity Probe B requires a supercooled environment for two reasons. First, all the fused quartz components (gyroscopes, housings, telescope) must be kept constantly cool to increase their molecular stability. Changes in temperature could cause the components to expand, and expand differentially. The gyroscopes could become unbalanced, the telescope could become misaligned or out-of-focus, or the entire science instrument could warp slightly.

Second, Gravity Probe B depends upon the London moment phenomenon to monitor the orientation of the gyroscopes. The London moment works only with a superconducting metal. Pure metals, like niobium and lead, become superconductive only when they are supercooled, in the neighborhood of absolute zero (0 Kelvin, -273 Celsius). Therefore, the niobium coating on the gyroscopes must be supercooled to produce the London moment.

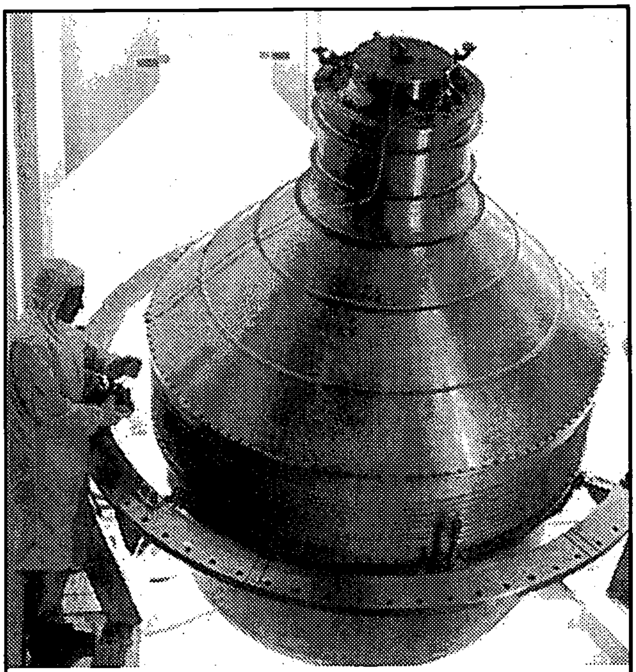


To ensure that the fused quartz components are stable and the London moment occurs, the GP-B science instrument will be cooled to nearly absolute zero - 1.8 Kelvin, or 271.2 degrees Celsius below zero.

How does Gravity Probe B create a supercooled environment, and keep it that way for 1-2 years? Creating a supercooled environment in a satellite in space is not that difficult, given how cold space is to begin with. The average temperature of space is calculated to be about 2.76 Kelvin, so space provides its own refrigeration.

However, *keeping* that satellite environment supercooled *for an extended time* is a major challenge. The GP-B satellite may be supercooled when it is in the Earth's shadow on the far side of the Earth from the Sun, but every time it orbits into the Sun's light its temperature will rise dramatically. The temperature fluctuations from one side of the Earth to the other are unacceptable for GP-B's science instrument to operate properly.

To maintain its supercooled environment of 1.8 Kelvin, Gravity Probe B designed a special dewar (or "Thermos") in which the science instrument rests. The dewar stands nine feet high and surrounds the science instrument with 608 gallons of liquid helium. (Helium gas becomes a liquid at temperatures below 9 K.)



The probe rests inside a 608-gallon, 9-foot tall dewar filled with liquid helium.

The success of the dewar in keeping the liquid helium and the science instrument supercooled depends upon several special devices, including a "porous" plug, multilayer insulation, vapor-cooled shields, and Passive Orbital Disconnect Struts.

The porous plug was invented at Stanford and engineered for space by NASA Marshall Space Flight Center and the Jet Propulsion Lab (JPL). As the liquid helium gradually boils and changes into gas during the two-year mission, the higher-temperature gas could mix with the lower-temperature liquid, speed the boiling process, and thereby reduce the amount of time in which the mission can operate.

The dewar has several systems designed to limit any changes in the temperature of the liquid helium or the science instrument, including

JAMES DEWAR

The "dewar" was invented by the Scottish scientist James Dewar in his pursuit of creating an "absolute zero" environment. In 1892, he produced the first dewar flask, which we generally call a "Thermos", and in 1898 he became the first person to liquefy helium at -254 degrees Celsius (only nineteen degrees Celsius from absolute zero!).

multilayer insulation (multiple reflective surfaces in the vacuum space to cut down radiation from the Sun), vapor-cooled shields (metal barriers, suitably spaced, cooled by the escaping helium gas), and Passive Orbital Disconnect Struts (PODS) (rigid launch supports, invented by Lockheed, which give looser support with less heat flow).

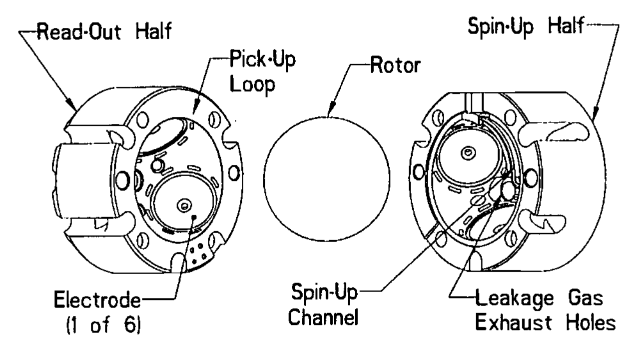
Despite the efforts of these systems, the liquid helium will slowly, yet inevitably, heat up and boil. As some of the liquid helium changes to gas, the (relatively) hotter gas will further heat up the remaining liquid. Liquid helium will then change to helium gas faster and faster, shortening the time that the GP-B science instrument will be accurate.

To slow down this heating process, a "porous" plug was invented at Stanford and engineered for space by NASA Marshall Space Flight Center and the Jet Propulsion Lab (JPL). The porous plug allows the helium gas to escape while locking the liquid helium inside, reducing the liquid's exposure to the (relatively) hotter gas, keeping the remaining liquid cooled longer. With the porous plug, the dewar temperature remains more uniform, instabilities from bubbles and "bump-boiling" vanish, and the helium lasts longer. The Gravity Probe B dewar will create a supercooled environment for a longer period than any other space satellite ever has.

2. Near-Zero Pressure, Near-Zero Magnetic Field

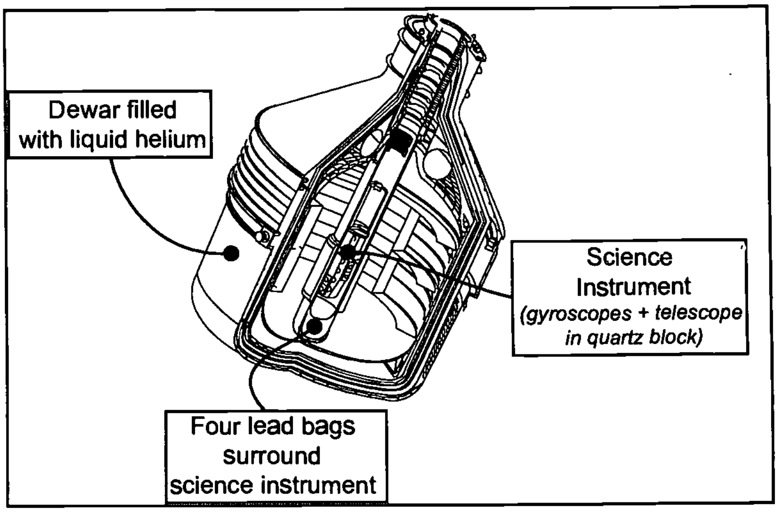
Inside the dewar, two other systems help create an near-zero environment for the science instrument.

The "pressure evacuation" system allows the gyroscopes to spin in a near-perfect vacuum, ensuring that friction from the air is non-existent. The gyroscopes spin at ~10,000 rpm, mere millimeters from the interior sides of each housing. After launch, each housing is evacuated to less than 10^{-11} Torr.



Each gyroscope, or rotor, spins at 10,000 rpm in a quartz housing, suspended by six electrodes.

The "lead bags" system protects the gyroscopes and the London moment from magnetic field interference. Within the dewar, four superconductive lead "bags" surround the science instrument. One at a time, each lead bag was placed inside the next one and expanded gradually. By expanding the bags and using four layers of lead protection, the possible magnetic field interference has been reduced to less than 10^{-14} gauss.



3. Near-Zero Acceleration: A Precise Orbit

It may appear that the satellite *is carrying* the gyroscopes around the Earth in a polar orbit. In fact, one of the gyroscopes is in a *free-fall orbit around the Earth.* This gyroscope acts as a "proof mass", laying out a near-perfect gravitational orbit. The satellite actually follows the orbital path of this gyroscope, and faces the difficult challenge of encasing this free-falling gyroscope without interfering with or touching it. Given that the gyroscope spins a mere millimeter from the edge of its housing, the satellite has very little margin for error.

For the most part, the satellite stays on course by following the same free-falling orbit. However, outside the satellite, two factors can alter the satellite's path. The solar radiation streaming from the Sun is enough to "knock" the satellite askew, and friction from atmospheric gases can slow the satellite down.

GP-B needs extremely sensitive thrusters to re-orient the satellite and keep it on its proper path. Here's where the escaping helium gas that slowly boils off from the liquid helium comes in handy. Minute amounts of gas, 1/10th of a human breath or a few millinewtons of force, provide just the right amount of thrust necessary to adjust the satellite's position. The thrust force of the escaping helium gas provides plenty of force to keep the GP-B satellite in its precise position (within 10 milliarcseconds of a perfect Earth orbit, pointing to within 1 milliarcsecond of the exact center of the guide star).

WHY LOW ORBIT?

Why does the GP-B satellite orbit so close to the Earth's atmosphere? Even at the edge of the Earth's atmosphere, the individual molecules and atoms of the atmosphere create too much friction for the satellite to follow its precise orbit. Why not orbit farther from Earth, outside its atmosphere?

The reason is that the effects of local spacetime (its curve and twist) weaken dramatically as one moves farther from the Earth. GP-B chose an orbit that would get it as close to the Earth as possible, to see the spacetime effects more clearly. A 400-mile altitude was the closest GP-B could get with a tolerable amount of atmospheric friction.

Concluding Questions

1) Will Gravity Probe B verify or refute Einstein?

Will the results of Gravity Probe B verify Einstein's theory of curved spacetime and frame-dragging, or will Einstein's theory be refuted? If the former proves true, then we will have made the most precise measurement of the shape of local spacetime, and confirmed to a new standard of precision the mathematics of Einstein's theory of general relativity. If the latter proves true, then we may be faced with the challenge of constructing a whole new theory of the universe's structure and the motion of matter.

2) Will Gravity Probe B reveal where "inertia" comes from?

One of the fundamental concepts of our physical world is that all objects at rest or in motion have inertia, or a tendency to keep doing whatever they are doing. But where does this tendency or property come from? Does is come from within matter itself? Or is it related to the underlying universe?

Physicist Ernst Mach proposed that the property of inertia comes from the motion of matter in the distant universe. The reason an object resists changes in motion is because it is somehow connected to the motion of all the other matter in the universe. It is a gravitational interaction that creates the property of inertia.

Gravity Probe B's investigation of frame-dragging will contribute to this question, because for distant matter to affect local matter, there has to be a gravitational link between the two. Einstein's theory of the geometry of spacetime and the effects of frame-dragging could explain this link.

Gravity Probe B is one of the most sophisticated physical experiments ever attempted. It has been in design for four decades and combines the efforts of dozens of scientists and engineers at Stanford University, Lockheed Martin Aerospace, NASA's Marshall Space Flight Center and VLBI scientists, along many others. It has spawned numerous advances in navigation technology and materials precision. And, most importantly, it will give us a glimpse into the sublime structure of our universe.

GRAVITY PROBE B
Classroom Extensions

"Seeing" Newton's Gravity with Marbles
An activity in which students attempt to observe the effects of gravity on a passing "comet" by rolling a ball bearing into orbit.

The Speed of Gravity
An activity in which students calculate the speed of light and compare their results with Newton's claim of "instantaneous propogation.

The Equivalence Principle
Four demonstrations in which students observe the Equivalence Principle in different ways with falling balls, pendulums, and thought experiments.

Spacetime Models
Models which demonstrate the concept of curved spacetime through the use of various materials.

Frame-Dragging of Local Spacetime
A simple activity in which students demonstrate the frame-dragging effect using a small ball, peppercorns, and a plate of honey. Yum!

The Microscopic Angles
Two activities in which students calculate the relative size of the angles that Gravity Probe B is attempting to measure.

Brief History of Gyroscopes
A short description of the origins of gyroscopes and how they were invented over the past milennia.

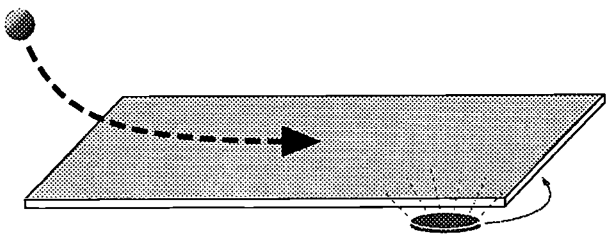
Contact Gravity Probe B at:
http://einstein.stanford.edu/
www@relgyro.stanford.edu

"Seeing" Newton's Gravity With Marbles

SUBJECT: **Observing Newton's Theory of Gravity**

Introduction: According to Newton's theory of gravity, all bodies possess the force of attraction called "gravity". Larger masses, such as the Sun, attract smaller masses, such as the planets and comets, more strongly, causing the smaller masses to move toward the larger masses. In our solar system, the planets orbit the Sun due to the force of the Sun's gravity pulling them into this elliptical path. Comets soaring through the galaxy are curved toward the Sun due to gravity's pull. In this demonstration, we use the force of magnetism to model how the force of gravity reaches out and pulls comets toward the Sun and how planets stay in orbit.

MATERIALS
- Flat Magnet (the stronger the better)
- Ball bearing (at least 8mm)
- Large piece of cardstock (~ 1ft.x 3ft.)



Setup: Place cardstock on table or floor. Place magnet underneath one end of the cardstock. Make sure the magnet does not create a significant bump in the card-stock. If it does, raise the cardstock so there is no bump.

Procedure: Roll a steel ball bearing down the length of the cardstock. Try to roll it near the hidden magnet. Observe what happens to the path of the ball bearing when it comes close enough to the magnet to react to its magnetic field. Can you make the ball bearing turn 45 degrees? 90 degrees? 180 degrees? 360 degrees? Try to roll the ball bearing at the right speed and distance from the magnet so it curls around it and comes back to you. This may take many efforts.

Observations:

1. What happens to the ball bearing when it...
   - √ Rolls near the magnet?
   - √ Rolls far from the magnet?
   - √ Rolls fast?
   - √ Rolls slow?

2. How should you roll the ball bearing to make it curl around the magnet? What speed, starting distance, path, or direction?

("Seeing" Newton's Gravity Cont.)

Connection Questions

1. What does the ball bearing represent? What does the magnet represent? What does the magnetic field represent?

2. How does the ball bearing "know" that the magnet is there? How does it "feel" the magnet's pull?

3. In what way is this model NOT an accurate demonstration of Newton's gravity?

Summary: The purpose of this activity is to demonstrate how planets orbit the Sun in Newton's theory of gravity. The magnet represents the Sun; its magnetic field represents the Sun's gravitational field. The ball bearing represents a planet moving near the Sun. It is a real challenge to get the ball bearing to bend around the magnet; it requires a specific speed and placement, as it does for a planet to go in orbit around the Sun. Most masses moving through our solar system either pass through or are drawn into the Sun.

The critical piece to understand from this demonstration is that Newton believed that planets respond to an invisible force called 'gravity'. They react in a manner similar to how metal balls react to magnets. The questions this should raise are: How does a planet "feel" the Sun's gravity? How does the planet know that the Sun is there? Additionally, how does the Sun's gravity reach out into space? Is it like light, which does not need a medium through which to travel, or like sound, which needs a material medium to travel? This activity is not designed to answer these questions. Rather, it is designed to uncover assumptions about gravity and raise the questions that Einstein had about gravity.

The Speed of Gravity?

***SUBJECT*: Calculating the speed of gravity and light**

Introduction: According to Newton's theory of gravity, the force of gravity reaches out across empty space instantly. Planets instantly feel the pull of the Sun's gravity. Baseballs instantly feel the pull of the Earth's gravity. However, this idea of a force instantly transmitting across space puzzled Einstein. In his special theory of relativity (1905), Einstein surmised that nothing could travel faster than the speed of light, including any energy or forces. And since light did not transmit instantly across the universe, how could gravity?

Procedure: Do the following calculations to see how long it takes light to travel from the Sun to each of the planets. Fill in the answers on the chart. In the last column, list one or two things that could occur in the time it takes light to travel from the Sun to each planet.

	Distance from Sun (km)	Speed of Light (km/s)	Time Elapsed (min)	Possible Event
MERCURY				
VENUS				
EARTH				
MARS				
JUPITER				
SATURN				
URANUS				
NEPTUNE				
PLUTO				

(The Speed of Gravity? Cont.)

Connection Questions

1. Does light travel instantly across the universe? Does light travel instantly across your classroom?

2. How long does it take for light to transmit from the nearest light bulb to this paper? Estimate the distance and calculate.

3. How fast does the magnetic force transmit? How long does it take for a magnet to reach a paper clip 1 cm away from it? Calculate.

4. How fast does the force of gravity transmit? As fast as light? Faster than light? Instantly?

5. Who do you think is right, Newton or Einstein? Does gravity transmit instantly and cause the planets to orbit, or is gravity limited to lightspeed, meaning something else causes the planets to curve around the Sun? What else could it be?

Summary: Einstein decided that due to this contradiction, and due to the Equivalence Principle, that gravity did not transmit as a force. Instead, the moons orbited planets, comets turned toward the Sun, and objects fell to Earth because the structure of spacetime was curved near masses. The objects themselves were not curving or moving in an elliptical path against the background of space; they were simply following the curves of local spacetime itself.

The Equivalence Principle

SUBJECT: **Four Demonstrations of the Equivalence Principle**

Introduction: According to Newton's theory of gravity, all objects fall to the ground because of the Earth's gravity. The Earth's force of gravity pulls the objects down as soon as they are released or fall off a table. But some interesting results happen when we drop two masses simultaneously. When we compare these results with what happens in outer space, we are introduced to the Equivalence Principle which states that physics in a gravitational field, like here on Earth, are equivalent to physics in an accelerating spaceship. Acceleration due to gravity or due to one's frame of reference accelerating are indistinguishable.

DEMONSTRATION #1 - THOUGHT EXPERIMENT

Procedure: Imagine you and a friend are each pushing identical wagons across a building roof. Your friend's wagon is empty while your wagon is filled with cement. You start pushing them at the same time and you push them at the same rate across the roof. You both reach the edge of the roof at the same time, and the wagons fall to the ground below.

Observations:

1. Which wagon is heavier?
2. Which wagon takes more force to push across the roof? (Remember, F=ma).
3. When the wagons fall to the ground, which hits the ground first? The heavier one or the lighter one?
4. Did gravity pull on each wagon with the same amount of force?

(The Equivalence Principle Cont.)

DEMONSTRATION #2 - BALL DROPS

Setup: Collect several pairs of objects that are about the same size but different weights. For example, a regular golf ball and a plastic golf ball, a tennis ball and a baseball, an empty plastic soda bottle and a full plastic soda bottle. Find a partner and take the objects to an empty space where you can drop them safely.

Procedure: Stand on a stepladder or stable, sturdy chair to drop the objects from a high point. (This will give you more time to observe them fall to the ground.) Hold them out at shoulder height and drop each pair simultaneously. Repeat several times with all objects.

Observations:

1. Which objects hit the ground first? The heavier or the lighter? Or do they hit simultaneously?

2. Do the objects fall at the same rate? Why or why not?

DEMONSTRATION #3 - PENDULUM SWINGS

Setup: Find a place to hang and swing a paper cup. You can attach it to the top of a doorway, to a test tube holder, to the edge of a table, to a basketball backboard, to a pipe, or to a tree limb. Tie a length of fishing line to a paper cup and attach it to the doorway (or whatever you use). Make the cup hang as low as possible without hitting the ground. Then tie a second cup and attach it. Make sure it is the exact same length. Now collect materials of different mass that you can put in each cup (e.g., sand, popcorn, dirt, rocks, paper, peanuts, cooked beans, raw beans, etc.)

Procedure: Fill each cup with materials of different masses, so that one cup is significantly heavier than the other (make sure not to overfill the cup to the point that the fishing line detaches). Slowly swing the two cups back and forthuntil the fishing line is nearly horizontal. Do not go any higher if the materials start to fall out. Release the cups simultaneously. Observe which cup reaches the bottom of the arc first. Repeat several times with different materials.

Observations:

1. Which cup reaches the bottom of the arc first? The heavier or the lighter? Or do they reach it simultaneously?

2. Do the cups fall at the same rate? Why or why not?

(The Equivalence Principle Cont.)

Summary A: From these demonstrations, you should see that all objects fall to the ground at the same rate, regardless of their mass. They accelerate at the same rate and hit the ground simultaneously. This is counter-intuitive because we assume that heavier objects fall faster since heavier objects hit the ground with more force. This often appears true in our experience because air resistance tends to slow the fall of lighter objects more than heavier objects, making heavier objects appear to fall faster.

Einstein was puzzled by this "simultaneous acceleration" principle because it meant that somehow gravity, which caused the objects to fall, must be pulling on each object with a different amount of force. (Heavier objects require more force to accelerate because they have more inertia.) But how could a force, such as gravity, "know" to pull on different size masses with a different amount of force, and pull with the exact amount to make them all fall at the same rate? The amount of gravity around the Earth determined by the mass of the Earth, which does not change significantly. So how could two unequal masses fall at the same rate?

We must take a look at gravity from outer space to understand this phenomenon...

DEMONSTRATION #4 - SPACESHIP THOUGHT EXPERIMENT

Procedure: Stand on a stepladder or stable, sturdy chair again, as in Demonstration #2. Take just one ball this time. Hold it out at shoulder height and get ready to drop it. But hold on...

Before you drop it, imagine you are floating in a spaceship in outer space, far from any gravitational fields. Imagine that the ball you are holding is actually floating next to you. There is no gravity in outer space, so neither you or the ball fall to the ground.

Now, do two things at the same time. Release the ball, and imagine that your spaceship just accelerated upwards at 9.8 m/s^2. Repeat this several times until you can really imagine that the engines are accelerating you upwards at the same instant that you release the ball.

1. What happens to the ball?

2. Does the motion of the ball look different to you in the spaceship than it does here on Earth?

3. What do you think the laws of physics are like in a spaceship accelerating at 9.8 m/s^2? Would it be harder to walk or play catch or climb stairs or jump than here on Earth?

(The Equivalence Principle Cont.)

Summary B: What you see in the accelerating spaceship is identical to what you experience here on Earth. This is the Equivalence Principle. Gravity is acceleration; the effects of each are equivalent and indistinguishable. When objects fall here on Earth, they are not being pulled down by the force of gravity. They are simply accelerating at the same rate, without being pulled by any force. Why do they all fall toward the Earth, even from different sides of the Earth, if there is no attractive force? Because, Einstein theorized, spacetime around Earth is warped toward the center of the Earth, and objects "fall" because they are following the structure of spacetime.

Spacetime Models

SUBJECT: **Making Models of Spacetime**

Introduction: According to Einstein's theory of general relativity (1916), motion in the universe is determined by an invisible, intangible structure of spacetime. Near sources of mass-energy (planets, stars, galaxies, black holes), spacetime is curved causing planets and moons to orbit and light to curve. It is extremely difficult to visualize the four-dimensional structure of spacetime; the following models attempt to provide a clearer picture of it.

Model #1 - Flat and Curved Surfaces

Materials -- soccer ball, flat area, sloped area

The simplest way to visualize curved spacetime is by comparing the paths of a ball on a flat surface and a sloped surface.

1. Roll a ball across a flat surface, such as a sidewalk. Imagine that the surface "grips" the ball in some unknown way, forcing the ball to follow its shape. The ball cannot rise above the sidewalk, or go below the sidewalk - it must follow the sidewalk's flat shape.

2. Roll the ball from a flat surface to a sloped surface. For example, some paved parking lots are flat in some parts and sloped in others. A field next to a hill will work as well.

3. Note how the ball follows the surface as if the surface is gripping the ball. The ball rolls flat where the surface is flat. The ball curves up where the surface curves up. Note that the ball does not continue going straight when the surface curves up. The ball is "gripped" by the curved surface, causing the ball's path to change. No outside force caused this change; it was simply a change in the surface.

4. Now imagine this happening in spacetime. As a ball, or a comet, travels through space, it follows the curves and the flats of spacetime. Where spacetime is flat the ball travels straight. Where spacetime curves, near a mass such as the Earth or Sun, the ball follows the curve. The ball can no longer go straight because spacetime "grips" it.

(Spacetime Models Cont.)

Model #2 - Flat and Curved Bedsheet

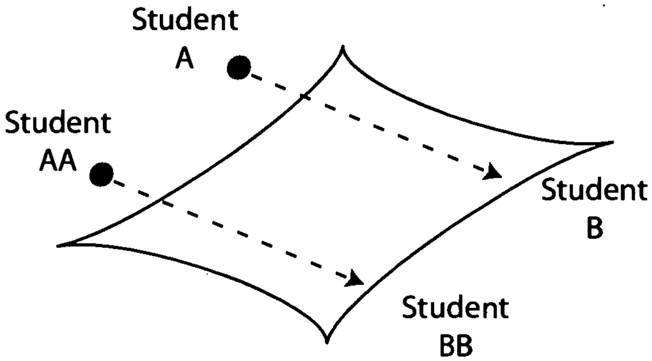
Materials -- bedsheet, several small balls, large weight

1. Hold a bedsheet flat and taut. (A "stretchy" sheet or blanket works best.) Have students stand around the bedsheet.

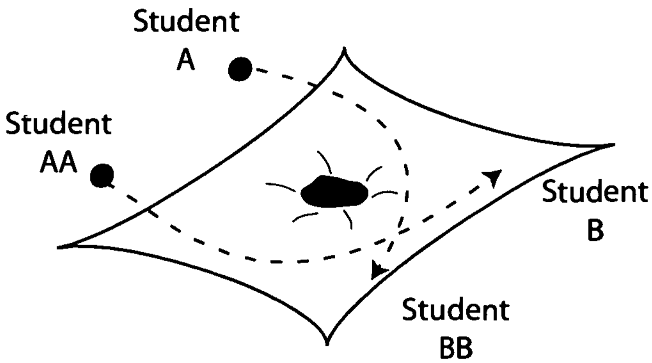
2. Roll several small balls back and forth across it. Observe their paths. The balls roll straight across the sheet. If Student A rolls a ball across the sheet toward Student B, the ball rolls straight to Student B - its path does not change.

3. Now place a heavy ball or weight in the center of the bedsheet. Hold the sheet taut, but let it sag in the middle where the weight is.

4. Roll the small balls across the sheet again. Observe their paths. This time, if Student A rolls a ball across the sheet toward Student B, the ball curves away from Student B - its path does change. Try and make the balls curve around the weight in some kind of orbit.



Why do the balls curve around the weight? Because they have no choice! In this model of spacetime, as the balls roll across the sheet, they are "gripped" by the sheet. Whatever shape the sheet takes, the balls will follow. In areas of space where the structure is flat, the balls roll straight. In areas of space near masses, spacetime curves and the balls curve with it.



Frame-Dragging of Local Spacetime

***SUBJECT*: Demonstration of frame-dragging**

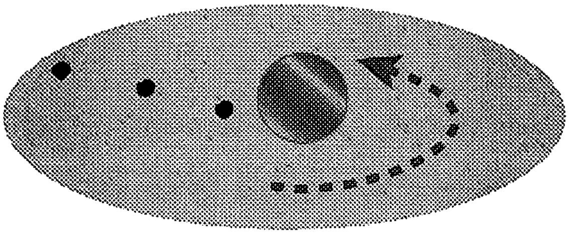
Introduction: One of the predictions of Eainstein's general theory of relativity is that local spacetime is twisted by the rotation of the Earth. Hans Thirring and Joseph Lense called this "frame-dragging" - any rotating mass will drag the local spacetime frame of reference with it. The predicted drag is very small and fades as one travels farther from the rotating mass, but the twist nearby can affect the paths of light, energy, and other masses.

MATERIALS
- Small paper plate (5 - 10")
- Small ball (a superball)
- Honey or molasses
- Peppercorns
- Food coloring

Setup: Each group needs a paper plate, honey, a superball, and 3-4 peppercorns.

Procedure:

1. Pour a layer of honey on the plate. It should be enough to form a sizeable puddle on the plate that is several times wider than the superball.



2. Place the ball exactly in the middle of the puddle.

3. Place 3-4 peppercorns in the honey, evenly distributed from the edge to the center (near the ball).

4. Squeeze 2-3 drops of food coloring in the honey around the ball. (Note: don't put the food coloring in the honey until you are ready to start twisting, as it will diffuse through the honey too much.)

5. Twist the superball at different speeds while keeping it in the middle of the plate. Continue for several minutes.

6. Observe the effects of the twisting ball.

Observations:

1. What happens to the honey? To each of the peppercorns?
2. How does the honey react differently near the ball than far from the ball?
3. What happens when you twist the ball at different speeds? How does the honey react differently?

Connection Questions

1. What did the parts of the model represent? The ball? The honey? The peppercorns? The food coloring?
2. What is the "local spacetime frame" in the demonstration?
3. Where does the "frame-dragging" occur in the demonstration?
4. What causes the "dragging" in the model?
5. Why do each of the peppercorns react differently to the twisting ball?

(Frame-Dragging Cont.)

Summary:

The purpose of this activity is to demonstrate how the Earth twists the local spacetime frame, but does not affect a distant spacetime frame. The ball represents the Earth, the honey represents spacetime, and the peppercorns represent other masses (stars, planets, etc.) in the spacetime frame at various distances. The food coloring is used to highlight the honey's motion, and does not represent an astronomical object.

A major limitation of this model is that the Earth spins much faster than you can twist the ball (~1,000 mph), and the spacetime frame spins much, much slower (~10^{-9} mph) relative to the Earth's rotation than the honey moves relative to the ball's rotation.

The rotation of the Earth does twist the spacetime frame like the ball twists the honey, although it is not caused by "friction" between the Earth and local spacetime. It is unclear to scientists exactly how this phenomena occurs. The theory of general relativity suggests that spacetime and masses have a mysterious mutual "grip" on each other.

Extension:

To illustrate the effect of twisting spacetime on a gyroscope's spin axis, repeat the activity with a piece of rice substituting for the peppercorn near the ball. Point the piece of rice at the peppercorn on the edge of the honey. Spin the ball and observe the piece of rice. Does it point in a new direction after a few turns of the "Earth"?

The Microscopic Angles

SUBJECT: **Understanding how small these angles are**

Introduction: Gravity Probe B must measure two microscopic angles. It is difficult to imagine how small these angles actually are. In part one, you will get a sense of how small these angles are. In part two, you will get a sense of how small GP-B's margin of error is.

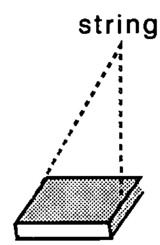
MATERIALS
- Large book
- String/fishing line (~20ft.)
- Tape
- Protractor

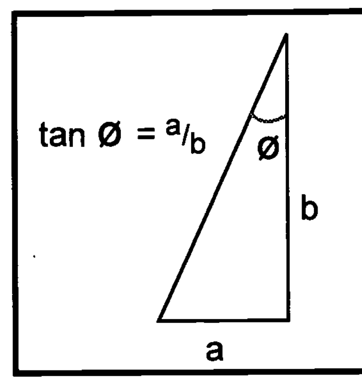
PART ONE

Setup: Put a textbook on the floor. Take a piece of string or fishing line (~20 ft.). Tape each end to the ends of the book so the string forms a triangle coming up from the floor.

Procedure:

1. Hold the string so that the peak of the triangle is 30 cm off the floor. Use a protractor to measure and record the angle at the peak. Repeat this measurement at four more heights, going as high as you can.
2. Use the tangent equation to calculate the size of the peak angle if you could stretch the string out many kilometers.





Height from floor	Angle at triangle peak
30 cm	
50 cm	
1 km	
25 km	
5000 km	
385,000 km (distance to Moon)	

Connection Questions:

1. What happens to the size of the angle at the peak of the triangle gets farther from the floor?
2. What is the ratio of change between the height and the angle? (i.e. for every 1 meter of height, how much does the peak angle change?)
3.. Why does the size of the angle change when you make the legs of the triangle longer?
4. How tall does the triangle need to be to create a peak angle of 42 milliarcsecondsseconds (1.16×10^{-5} degrees)?

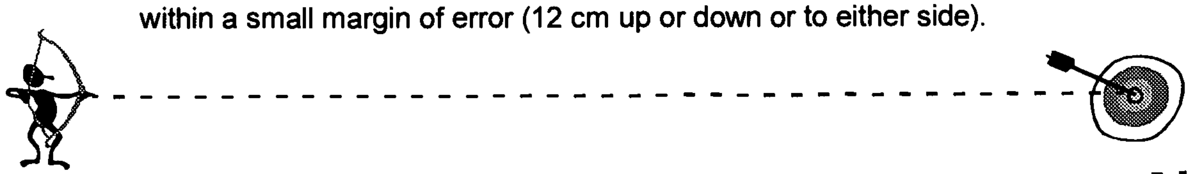
(Microscopic Angles Cont.)

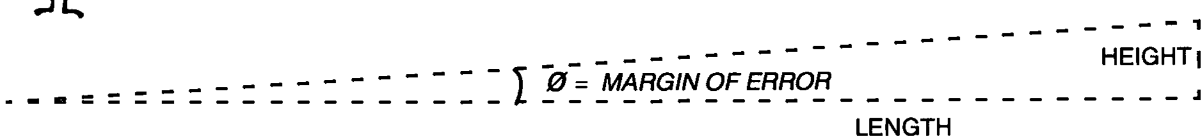
PART TWO

Introduction: Gravity Probe B is trying to measure two microscopic angles - 6.6 arcseconds and 42 milliarcseconds. To make these measurements, they need to measure them very precisely. The acceptable margin of error is 0.5 milliarcseconds. In other words, GP-B cannot simply say that the angle is closer to 42 milliarcseconds than 43 or 41 milliarcseconds. They have to say that it is closer to 42.0 milliarcseconds than 42.1 or 41.9 milliarcseconds.

Procedure:

1. Imagine you are an Olympic archer. You stand 100 meters away from a target and you aim for the bullseye. The bullseye of the standard target is 24cm in diameter. In order for you to hit the bullseye, you must fire the arrow straight within a small margin of error (12 cm up or down or to either side).





2. Calculate your margin of error in degrees. Draw the triangle between you and the target. The length of the triangle is 100 m. The height of the triangle is 12 cm. The tangent of the "margin of error angle" is the height divided by the length. Find the angle size.

3. The margin of error for GP-B is only 0.5 milliarcseconds (2.7×10^{-7} degrees). Calculate how large the "bullseye" is for Gravity Probe B at 100 meters.

4. Imagine the target was moved to the Moon. At 385,000 km away, how large is the bullseye for GP-B now?

Distance from target	**Maximum height** *(i.e., margin of error to either side)*	**Tangent Ø = distance / height**	**Ø = ??**
100 m	12 cm		
	12 cm		0.5 milliarcseconds
385,000 kim (distance to Moon)			

Brief History of Gyroscopes

***SUBJECT*: History of the Gyroscope**

Introduction: Gravity Probe B has made one of the most sophisticated and accurate gyroscopes in the world to measure the shape and motion of local spacetime. Yet, their gyroscopes have much in common with the simplest toy tops that children have played with for centuries. The spinning top retains its balance through a physical phenomenon called "precession". Without this phenomena, there would be no toy tops or Gravity Probe B.

History: In early times, people discovered the spinning top, a toy with a unique ability to balance upright while rotating rapidly. Ancient Greek, Chinese and Roman societies built tops for games and entertainment. The Maori in New Zealand have used humming tops, with specially-crafted holes, in mourning ceremonies. In 14th century England, some villages had a large top constructed for a warming-up exercise in cold weather. Tops were even used in place of dice, like the die in the contemporary fantasy game Dungeons & Dragons.

It was not until the late 18th and early 19th centuries that scientists and sailors began attempting to use spinning tops as a scientific tool. At that time, sailors relied on sextants for navigation, measuring the angle between specific stars and the horizon. This method was limited, however, if choppy seas or fog obscured the true horizon, or clouds obscured the stars.

Serson, an English scientist, noted in the 1740's that the spinning top had a tendency to remain level, even when the surface on which it rested was tilting. He suggested that sailors could use it as an artificial horizon on ships. Unfortunately, when Serson went to sea to test this idea the ship sank and everyone was lost.

A French scientist in the 19th Century, Fleuriais, created a top that was continuously powered by air jets blowing into mini-buckets on the rim of the wheel – a process that has been used for thousands of gyros since. The first modern gyroscope was designed in 1810 by G.C. Bohnenberger. It was made with a heavy ball instead of a wheel, but since it had no scientific application, it faded into history.

In the mid-19th century, the spinning top acquired the name, "gyroscope," though not through its use as a navigation tool. French scientist Leon Foucault had experimented with a long, heavy pendulum in an attempt to observe the rotation of the Earth. The pendulum was set swinging back and forth along the north-south plane, while the Earth turned beneath it.

(History of Gyroscopes Cont.)

Foucault corroborated the observation by using a spinning top in a similar manner. He placed a wheel, rotating at high-speed, in a supporting ring in such a way that the axis of the spinning wheel could move independently of the ring. In fact, the supporting ring moved over the course of a day, as it was connected to the surface of the rotating Earth. The axis of the wheel remained pointed in its original direction, confirming that the Earth was rotating in a twenty-four hour period. Foucault named his spinning wheel a "gyroscope", from the Greek words "gyros" (revolution) and "skopein" (to see); he had seen the revolution of the Earth with his gyroscope.

Fifty years later (1898) Austrian Ludwig Obry patented a torpedo steering mechanism based on gyroscopic inertia. It consisted of a little bronze wheel weighing less than 1.5 pounds that was spun by an air jet (like Fleuriais). In the early 20th Century, Elmer A. Sperry developed the first automatic pilot for airplanes using a gyroscope, and installed the first gyrostabilizer to reduce roll on ships. While gyroscopes were not initially very successful at navigating ocean travel, navigation is their predominant use today. They can be found in ships, missiles, airplanes, the Space Shuttle, and satellites.

Books, Articles, and Web Sites

BOOKS & ARTICLES

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Relatively Speaking by Eric Chaisson, 1988.

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"**Around-the World Atomic Clocks: Predicted Relativistic Time Gains**" and "**Around-the-World Atomic Clocks: Observed Relativistic Time Gains**" by J.C. Hafele and Richard Keating. Science Magazine, vol.177, pgs.166-170, July 1972.

WEB SITES

Gravity Probe B: The Relativity Mission
http://einstein.stanford.edu/

NASA Spacelink -- An Aeronautics & Space Resource
http://spacelink.nasa.gov/index.html

How Gyroscopes Work
http://www.howstuffworks.com/gyroscope.html

Albert Einstein Online
http://www.westegg.com/einstein/

Satellite Test of the Equivalence Principle
A Cultural History of Gravity and the Equivalence Principle
http://einstein.stanford.edu/STEP/gravityhist2.html

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EFF-089 (3/2000)