Einstein and Gravity Probe B

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The Institute of Mathematical Sciences, Chennai
Organization of the Talk

- What is Gravity Probe B?
- General Theory of Relativity
- Predictions for Spinning test bodies
- The Experiment
- Remarks
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http://einstein.stanford.edu/
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the geodetic precession due to ’curvature’ and

the frame dragging precession due to spinning of the earth.
What is the General Theory of Relativity?

It is a synthesis of three different notions/facts, namely,

1. The notion of space and time,
2. Riemannian geometry and
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Special Theory of Relativity accepts as postulate, that the speed of light in vacuum is constant. Instantaneous communications are out and space and time merge into the single entity called space-time.
Space + Time $\rightarrow$ Space-Time

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Riemannian Geometry

Space (or space-time) also has Geometrical properties such as lengths of solid rods, sums of angles of triangle etc. The geometrical properties can be encoded in terms of a metric or a rule specifying length of a coordinate interval. These are Riemannian geometries which are curved in general. Pre 1905, the space is flat (Euclidean). Between 1905 and 1915, the space-time is still flat (Minkowski) but now moving lengths contract and clocks slow down. A rotating observer will measure the geometry to be non-Euclidean due to the length contraction effects.
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Gravity

A curious fact: gravitational mass = inertial mass.

Uniform gravity is indistinguishable from uniform acceleration!

But, acceleration affects geometry, so gravity affects geometry!!

But, matter/energy produces gravity, so matter/energy also affects geometry!!

GTR: Matter moves in a curved Riemannian manifold whose geometry is determined by the matter distribution.
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Novelties of GTR

- Light bends around massive bodies (confirmed);
- Planetary orbits precess (confirmed);
- Stars can collapse to form black holes (widely believed);
- Gravitational waves (indirect evidence);
- "Big Bang cosmology" (widely believed);
- A small spinning body would precess due to curvature near a massive body and an additional precession if the body is rotating (Being tested!).
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If a half filled bucket is set spinning, the water starts spinning too and its surface becomes curved. What is this rotation relative to?

It can't be the relative rotation between water and the bucket walls. Newton favored Absolute space, others favored Distant stars! (Mach, 1893)

If the distant stars rotated and not the bucket, would the surface be curved?

Mach may have realized that notions of inertia, dynamics be such that with either view, the surface should be curved – Mach
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In GTR, this is possible since a rotating universe will have a different geometry which will curve the water surface [Brill-Cohen (1966), Pfister-Braun (1985)].
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It is hard to rotate the whole universe or go very close to a rotating black hole, but we can just watch a spinning gyroscope falling freely around the rotating earth.

This is just what Gravity Probe B Experiment is.
Basic Equation for Spin precession

\[ d\vec{S} = \langle \vec{\Omega} \rangle \times \vec{S} , \quad \langle \vec{\Omega} \rangle = \frac{G_2}{r^3} \left[ \vec{J}_E - \hat{h} (\hat{h} \cdot \vec{J}_E) \right] + 3 \left( \frac{GM_E}{2} \right)^{3/2} \frac{1}{r^{5/2}} \hat{h} \]
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\frac{d\vec{S}}{dt} = \langle \vec{\Omega} \rangle \times \vec{S},
\]

\[
\langle \vec{\Omega} \rangle = \frac{G}{2r^3} \left[ \vec{J}_E - \hat{h}(\hat{h} \cdot \vec{J}_E) \right] + \frac{3(GM_E)^{3/2}}{2r^{5/2}} \hat{h}
\]
Basic details and Estimates

- Polar circular orbit with $r \sim 400$ miles;
- Duration of experiment $\sim 12 - 14$ months;
- Estimated Geodetic precession rate $\sim 6.6$ arcsec/yr;
- Estimated Frame-dragging precession rate $\sim 40.9$ milliarcsec/yr;
Experimental Requirements

Basically, all sources which could induce precession must do so with amount less than the estimate and since the change is so minute, the detection of the changes must be extremely precise.
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3. Stable reference to a Guide Star;
4. Trust worthy Guide Star;
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1. Gyroscopes must be stable and drag-free;
2. Method to read the spin direction without disturbance;
3. Stable reference to a Guide Star;
4. Trust worthy Guide Star;
5. Isolating Relativity Effects;
6. Calibration Scheme.
The arrangement
The Gyroscope

- Pure quartz ball of diameter 3.81 cm, spherical within few atomic layers \( (<3 \times 10^{-7} \text{ inches}) \), homogeneous within \((10^{-6})\), electrical dipole moment vanishingly small;
- Coated with Niobium, suspended electrically in its housing with a clearance of \(10^{-3} \text{ inches}\), remains centered within \(10^{-6} \text{ inches}\). Spin rate up to 10,000 RPM;
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Detecting spin direction: London moment induced in the rotating super-conductor. Read by a SQUID with sensitivity of $10^{-14}$ gauss. Cut earth’s magnetic field by $10^{-13}$ by enclosing in lead bags;
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Spin-up is achieved by evaporating super-fluid Helium passing around the gyroscope.
Guide Star

Ideally should be a quasar – too faint;

Star with known motion relative to a quasar, preferably a binary with a radio source;

convenient position in the sky – IM Pegasi;
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Telescope

- Should detect changes of $10^{-4}$ arcsec;
- Telescope should remain exactly pointed at the center of the star's image despite diffraction – split image;
- 5.6 inch diameter, 4 inch length, made up from quartz elements with optical contact.
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Near Zeros

Temperature: $1.8^0 \text{ K}$

Pressure: $< 10^{-11} \text{ Torr}$

Gravitational Acceleration: $< 10^{-10} \text{ g}$

Material homogeneity: $< 3 \times 10^{-6}$

Mechanical sphericity: $< 3 \times 10^{-7} \text{ inch}$

Electrical sphericity: $< 5 \times 10^{-7}$

Magnetic field: $< 10^{-6} \text{ Gauss}$
Remarks

This experiment, conceived over 40 years ago, illustrates a number of points:

▶ Even for a universally believed theory, there is a qualitatively distinct prediction, which is yet to be confirmed and is being tested;
▶ The predicted deviations are tiny making the tests very much harder calling for tremendous sophistication;
▶ Yet, it is worthwhile to devise experiments, even if only to test very esoteric ideas, since they spur new technological developments.
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Thank You