

New twist on gravitational spin?

From **Bernard Schutz** in the Albert Einstein Institute, Potsdam, Germany, and the Department of Physics, University of Wales, Cardiff, UK

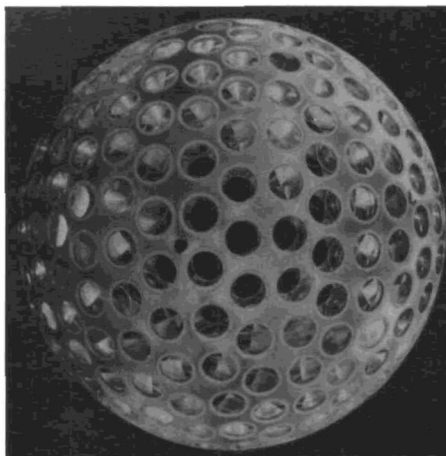
ONE of the last predictions of Einstein's general relativity not yet confirmed by observation or experiment may have yielded to careful measurement. Einstein predicted that the spin of the Earth should create a gravitational field that affects other rotating objects. This field should, among other things, cause gyroscopes to precess. NASA is planning to launch the Gravity Probe-B mission in 1999 to measure this precession and hence verify Einstein's prediction.

This gravitational effect should also cause the orbital planes of satellites to rotate, and Ignazio Ciufolini of the University of Rome "La Sapienza" and colleagues have now measured the effect by precisely tracking the orbits of satellites launched for other purposes (*Europhys. Lett.* 1997 **39** 359; *Class. Quant. Grav.* 1997 **14** 2701). If confirmed, this will be a landmark in experimental gravitation and another key test of general relativity. It may also open a Pandora's box of questions about the formulation of national and international science policy.

The spin of an object affects both the spin and orbit of a body orbiting it, an idea that is familiar from atomic physics. Indeed, it is simple to calculate the spin-spin and spin-orbit corrections to the energy levels in the hydrogen atom. These corrections arise through magnetic interactions. The spinning nucleus is like a little dipole magnet, and this exerts a small force on the orbiting electron. The spin of the electron is also a dipole magnet, so it experiences a force from the nuclear magnetic field.

These effects have close analogues in gravitation. This is because special relativity makes it possible to "derive" magnetism from a static electric force. The source of an electric field is essentially the electric charge density, but the volume occupied by the charge changes when it is viewed by a moving observer. This alters both the charge density and the electric field, but the effect of the field on a test charge must be independent of the observer. This means that there has to be another force that depends on the motion of the source charge – this is what we call magnetism. The *Feynman Lectures* provide a particularly simple and elegant derivation of magnetism in this way.

Given this, it is not surprising that a combination of special relativity and Newtonian gravity, which resembles Coulomb's electrostatics, can produce magnetic-like gravitational effects. Such an approach leads to an effect called gravitomagnetism, which says



Mirror ball – NASA's LAGEOS satellite

that a moving body will experience an additional non-Newtonian gravitational force from another moving mass. If this mass is spinning, gravitomagnetism acts in a similar way to a magnetic dipole field, and the effect on an orbiting body is known as the Lense-Thirring effect. Similarly, two spinning masses exert extra forces on each other.

The magnitude of the Lense-Thirring effect depends on the theory of gravity. This is because the derivation of magnetism from the Coulomb force needs a rule to define how the source of the field (the "charge") depends on speed. In electromagnetism, a particle's charge is assumed to be independent of its speed, so the charge density only changes because the volume changes, leading to standard magnetism. In Newtonian gravity, the source of the field is basically the mass of the particle. This is ambiguous in relativity: should it be the rest mass, which is the same for all observers, or the total mass-energy, which increases with speed?

Different relativistic theories of gravity adopt different formulations for the relativistic charge, and thus for the way that it changes with speed. In Einstein's general theory, the relativistic charge increases with speed, and the gravitomagnetic effects are relatively strong. In a scalar theory of gravity, however, the source strength actually decreases with speed, and gravitomagnetic effects are completely absent.

Since the Lense-Thirring effect depends on the gravitational theory, a long-standing goal has been to measure the effect and test the predictions of Einstein. Since the effect depends on the speed of the source, one would naturally look for the most relativistic conditions possible. Black holes provide such conditions, and the effect seems to have been observed in recent X-ray astronomical data. Unfortunately, these data and the models used to interpret them are not precise enough to make a quantitative test of

general relativity.

Controlled tests are easier if we use the spin of the Earth, rather than a black hole, but the gravitomagnetic field is so weak that ground-based experiments are difficult (but not impossible). One must therefore either launch a space-based laboratory like Gravity Probe-B (GP-B) or observe the orbits of satellites with great precision.

Using existing satellites is the cheaper alternative, but has a big disadvantage. Gravitomagnetism affects satellites orbiting the Earth in two main ways: it "drags" the orbital plane of the satellite in the direction of the Earth's rotation, and it causes the point of closest approach within the orbital plane (perigee) to precess. However, both of these effects are also produced by certain non-spherical parts of the Earth's gravitational field. To measure the relativistic effects, one must somehow subtract the much larger Newtonian effects.

Ciufolini has been proposing a clever way of doing this for some years. Two satellites have been launched to measure the irregularities of the Earth's field: LAGEOS by NASA in 1976 and LAGEOS II in 1992 by the Italian Space Agency. The satellites are small and dense to minimize atmospheric drag, and are covered with mirrors. Ground stations around the world track these satellites to an accuracy of 1 cm or better by bouncing laser pulses off the mirrors.

Ciufolini has proposed the launch of a third satellite, LAGEOS III, into an orbit that is a mirror reflection of that of LAGEOS II. With opposite inclination and orbital angular momentum, the gravitomagnetic effects on LAGEOS III would be equal and opposite to those on LAGEOS II, while the Newtonian effects from the shape of the Earth would be the same. The gravitomagnetic Lense-Thirring effect could then be obtained directly by tracking the difference between the orbital planes.

However, no space agency has adopted the proposal for LAGEOS III, so Ciufolini decided to see what could be done with the existing two spacecraft and a model of the Earth's gravitational field. The important parameters of the field are the quadrupole moment due to the oblateness of the Earth, J_2 , and higher even moments (J_4 , J_6 ...), which represent the higher-order irregularities in the Earth's density and shape. These irregularities have been determined by laser ranging to the LAGEOS satellites and to other satellites, and values of the moments have been derived using a solution of the Earth's gravity field. However, the estimated uncertainties in J_2 and J_4 could create larger effects on the orbits of the LAGEOS satellites than gravitomagnetism itself.

Although this would seem to make the measurement hopeless, Ciufolini has found a way round the problem. Only the uncertainties in the first two moments are important, since the errors in the higher moments have a smaller overall effect than the Lense–Thirring effect, at least for the LAGEOS satellites. Ciufolini realized that the dominant errors in the orbits can be removed by using a number of independent orbital parameters. For example, the changing orientation of the satellite's orbital plane is affected by both gravitomagnetism and the errors in J_2 and J_4 , providing three unknowns. Because LAGEOS and LAGEOS II are in different orbits, this orientation is affected by a different linear combination of these unknowns. Moreover, the shifting position of the perigee of LAGEOS II also depends on these factors. These three orbital parameters therefore yield three equations that can be solved to provide a value for the effect of gravitomagnetism. (The motion of the perigee of LAGEOS is hard to measure accurately because its orbit is nearly circular and the perigee is poorly defined.)

Ciufolini and colleagues used a sequence of successive 15-day observations for their analysis, and compared the values obtained using different Earth-gravity solutions. Their measured value for the gravitomagnetic effect is 1.1 times the value predicted by general relativity, with an uncertainty of 30%. Systematic uncertainties, like the effects of atmospheric drag and solar radiation pressure, are the most difficult to measure. The ultimate acceptance of Ciufolini's measurements will hinge on a detailed examination of his corrections and error estimates for a host of systematic effects.

So what is the significance of this remarkable result? If the analysis stands up to scrutiny and the estimated uncertainties are

correct, Ciufolini and his collaborators will enter the textbooks as the first people to verify gravitomagnetism. If not, we will look to GP-B or improved X-ray observations for the real answer.

The measurement of gravitomagnetism would provide further confirmation of Einstein's prediction, which is vital for the interpretation of future X-ray and gravitational-wave data. On the other hand, a number of solar-system observations and experiments have tested general relativity, and have effectively verified that the source of gravity strengthens with speed, confirming Einstein's prediction and the Lense–Thirring effect. If we find that the effect does not follow Einstein's ideas after all, general relativity would have to be replaced with a radically different theory. Given relativity's success in other experiments, the outcome of the measurement is reassuring, but not unexpected.

What is the significance for the GP-B experiment? Now being built at Stanford University, this is one of the most ambitious and expensive scientific satellites ever attempted by a single university group (see the Web site <http://stugyro.stanford.edu/RELATIVITY/GPB/>). A set of superconducting gyroscopes in a liquid-helium dewar will be placed into orbit, and their weak precession will be sensed using Josephson junctions. As if that is not difficult enough, GP-B will pioneer the technique of drag-free control, which means that the critical parts of the experiment will float freely inside the satellite to shield them from environmental disturbances and ensure that the gyroscopes are only affected by gravity. This technique will be needed for later scientific missions, including the LISA gravitational-wave mission (see *Physics World* 1996 December pp25–30). GP-B will be able to measure the Lense–Thirring effect to accuracies better than 1%,

much better than the Ciufolini result.

Given the significant investment already made in GP-B, its superior capabilities and its importance as a technology demonstrator, it seems unlikely that the project will be derailed by the Ciufolini measurement. After all, few scientists would have expected GP-B to do anything other than verify Einstein's prediction. Moreover, it will take some time for the experts to assess Ciufolini's method and form a consensus about the validity of his claim, particularly the error estimate. But there can be no doubt that the satellite analysis has stolen some of GP-B's thunder.

The Ciufolini measurement is bound to cause unease about science policy. The expensive GP-B project started in the 1970s, but one wonders why no-one seriously considered an experiment like LAGEOS III until over a decade later. Was the cryogenic technology used for GP-B more highly developed in the 1970s than the laser technology required for LAGEOS? One also wonders why LAGEOS III has not had more success with space agencies. When NASA, after much wavering, confirmed its commitment to GP-B in 1994, it did not consider LAGEOS III to be serious competitor because GP-B would be more accurate. Ciufolini's present method, even with less accuracy, had not been suggested then. When LAGEOS III was considered by ESA, it failed partly because it was too cheap: at the time ESA had no program for very small scientific satellites.

Ciufolini's measurement is bound to reopen these questions, as well as many others about the lack of international co-ordination of science policy. It may be some time before we hear the final word on Ciufolini's error estimates. But if his measurement stands up to scrutiny, the other questions may be debated for even longer.

Fresh insights into electron oscillations

From **Hartmut Roskos** at the Institute of Physics, University of Frankfurt, Germany

IN 1934, during the early days of quantum mechanics, Carl Zener used the ideas of Felix Bloch to predict that the electrons in a crystalline solid would oscillate at high frequencies when subjected to a constant electric field. However, these so-called Bloch oscillations were not detected until five years ago, when their observation was made possible by the availability of semiconductor superlattices and ultrashort laser pulses. Now, for the first time, Karl Leo and colleagues at the Technical University of Dresden in Germany have used a novel optical technique to precisely determine the high-frequency electric field generated in the superlattice by the oscillating elec-

trons. From the data, they were able to derive the spatial dynamics of the electrons (V G Lyssenko *et al.* 1997 *Phys. Rev. Lett.* **79** 301).

The concept of Bloch oscillations has puzzled solid-state physicists ever since it was first proposed. It suggests that the conduction-band electrons in the periodic potential of a crystalline material move back and forth in a constant electric field, but do not move from the centre of oscillatory motion. If this were the case, an electric current would not flow when a voltage is applied, contrary to our experience.

This would happen if the electrons did not scatter from impurities, lattice vibrations or "phonons", other electrons and crystal imperfections. These scattering events happen so often that they disrupt the simple

oscillatory motion, giving rise to the "hopping" transport that leads to the current flow described by Ohm's law. Indeed, the scattering processes are so efficient that it has proved extremely difficult to detect Bloch oscillations.

The oscillations were finally observed in 1992 by Leo, Jochen Feldmann and Jagdeep Shah, then working at AT&T Bell Labs in the US, who used a sophisticated optical technique called time-resolved four-wave-mixing spectroscopy. Ultrashort laser pulses were used to excite Bloch oscillations and a probe laser pulse allowed the researchers to monitor the temporal dynamics of coherent electron wavepackets. Although these first measurements left some doubt as to whether the electron wavepackets were oscillating in space, myself and colleagues,