General relativity

Frame-dragging confirmed

Neil Ashby

According to a prediction of general relativity, the spinning mass of the Earth affects the motion of satellites. A measurement of this 'frame-dragging' effect confirms Einstein's theory.

General relativity predicts that a spinning mass distorts space-time — one of a variety of 'gravitomagnetic' phenomena that are absent in Newtonian gravity. Unfortunately, gravitational forces are so weak that it is useless to try to detect this warping of space-time unless the mass is very large and spinning rapidly — an astronomical body, say, such as the Earth or the Sun, or a neutron star. After many years' work, and through the analysis of millions of 'laser-ranging' measurements made from more than 50 Earth-based stations, Ciufolini and Pavlis[1] have confirmed the twisting effect of the spinning Earth on the orbits of two artificial satellites (page 958 of this issue). The remarkable precision they have achieved is due in large part to recent improvements in the modelling of Earth's gravitational field.

According to general relativity, a spinning flywheel imparts a twist to space and time in its proximity that can affect a nearby gyroscope. If a frictionless gyroscope is placed near the flywheel's axis of rotation, the gyroscope's spin axis will be dragged along in the direction of the flywheel's rotation. However, if the gyroscope is placed near the flywheel's perimeter, its spin axis will be dragged in a direction opposite to the flywheel's rotation. First analysed by Joseph Lense and Hans Thirring, soon after Einstein published his general theory of relativity, the phenomenon is known as the Lense–Thirring effect — or 'frame-dragging', because the spin axes of ideal gyroscopes could be used to track the directions of coordinate axes in an inertial reference frame.

Frame-dragging is one aspect of the class of relativistic phenomena loosely known as gravitomagnetism, through their analogy with the effects of ordinary magnetic forces on moving electric charges. General relativity describes gravity in terms of a set of ten independent quantities (the components of a second-rank tensor). The gravitomagnetic terms, however, vanish unless the mass producing the gravitational field is moving. Among the effects caused by gravitomagnetic forces are precessions (similar to the wobble of the axis of a spinning top) of the orbital plane of a satellite around a spinning body (such as Earth), or precessions of the orbit of an Earth satellite as the Earth–satellite system orbits the Sun. This latter effect is usually called de Sitter or geodetic precession.

Precise measurement of these effects predicted by relativistic gravity theories is crucial, as they have important implications for our view of the cosmos. Gravitomagnetic effects can be significant in many astrophysical systems. For example, in the binary pulsar B1913+16, geodetic precession of the orbits may cause the pulsed beam from this star to precess out of our line of sight in a few dozen years, and to reappear some centuries later[2]. However, the uncertainties in such distant systems are usually too large for astronomical objects to be used for precision tests of gravitomagnetic effects.

In the case of the Earth–Moon system, the Moon's orbit may be thought of as a gyroscope with its spin axis perpendicular to the Moon's orbital plane. A change in the direction of this axis can be measured by observing the change in the nodal angle; this is the angle between an astronomical reference line (the first point of Aries, in Earth's equatorial plane) and the line of intersection between Earth's equatorial plane and the Moon's orbital plane. According to general relativity, the geodetic precession of the nodal angle is only a little more than five-millionths of a degree per century, which amounts to motion of the node (on the orbit) of about 3 metres per month. This prediction has been verified[3] to an accuracy of about 0.7%, through many years of accurate laser ranging — bouncing laser signals off retroreflectors placed on the lunar surface by Apollo astronauts — and by the development of extremely sophisticated models of the perturbed orbital motion and rotations of the Moon. However, frame-dragging of the Moon's orbit caused by the spin of the Earth is negligible, because the effect falls off rapidly with distance and the Earth is not spinning particularly fast.

But near-Earth satellites suffer larger perturbations owing to gravitomagnetic effects. These perturbations are still extremely tiny, and require enormous effort to measure, as Ciufolini and Pavlis[1] have shown. The two satellites used in their analysis are LAGEOS and LAGEOS 2 (for Laser Geodynamics Satellite). LAGEOS was launched in 1976; the satellite is compact, completely passive, and consists of a heavy sphere covered with retroreflectors. LAGEOS 2 was launched in

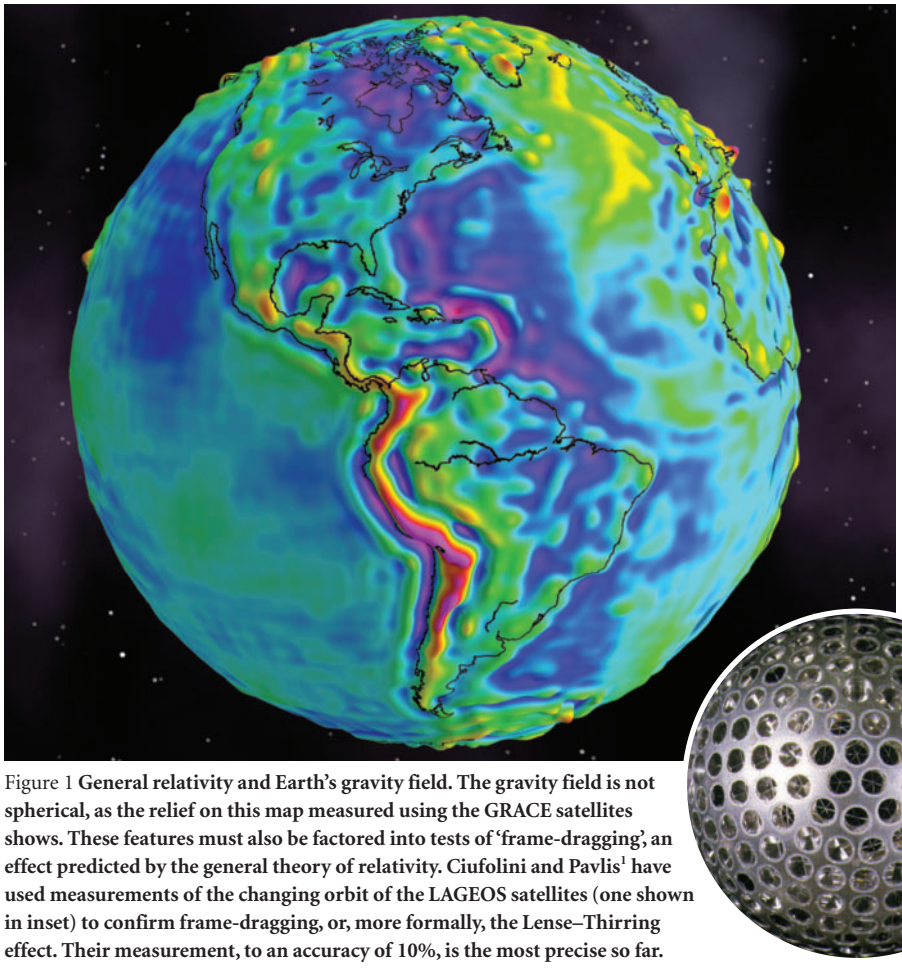

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Figure 1 **General relativity and Earth's gravity field. The gravity field is not spherical, as the relief on this map measured using the GRACE satellites shows. These features must also be factored into tests of 'frame-dragging', an effect predicted by the general theory of relativity. Ciufolini and Pavlis[1] have used measurements of the changing orbit of the LAGEOS satellites (one shown in inset) to confirm frame-dragging, or, more formally, the Lense–Thirring effect. Their measurement, to an accuracy of 10%, is the most precise so far.**

1992 from the Space Shuttle. Accurate laser ranging to these satellites is used to develop better models of Earth's gravity field. This field is not spherical, but has many ripples because of the variations in Earth's mass distribution (Fig. 1). As a result, any frame-dragging experiment must take account of large orbital perturbations that are a solely due to ordinary Newtonian gravity.

In fact, uncertainties in some of the ripples in Earth's gravity field are large enough to mask frame-dragging effects almost completely: for a satellite at an altitude of 12,000 km, frame-dragging of the node is only about 1.9 metres per year, whereas the nodal precession due to oblateness of the Earth is many thousands of kilometres per year. Geodesy missions such as CHAMP and GRACE[4,5], whose purpose is to further refine models of Earth's gravity field and study crustal motions, have been essential in reducing the uncertainties. Ciufolini and Pavlis[1] have used two observable parameters — the nodal precession rates of both LAGEOS satellites — to eliminate the principal uncertainty caused by Earth's oblateness. From the remaining data, which consist of more than 100 million laser-ranging observations between Earth and the satellites, the frame-dragging effect could be measured.

The result — the first reasonably accurate measurement of frame-dragging — confirms the general theory of relativity to within a conservative error estimate of 10%. Further analysis is anticipated as additional geodesy missions are undertaken to improve our knowledge of Earth's gravity field. And results are eagerly awaited from NASA's Gravity Probe B, which was launched into polar orbit in April this year. This satellite had been under development for more than 40 years, and seems to be performing well. Its array of gyroscopes and readout systems should produce an even more precise measurement of gravitomagnetic precession, to an accuracy better than 1%. Precise observations of such theoretical predictions will improve our understanding of the cosmos. In all experiments performed up to now, general relativity has been accurately confirmed. ■

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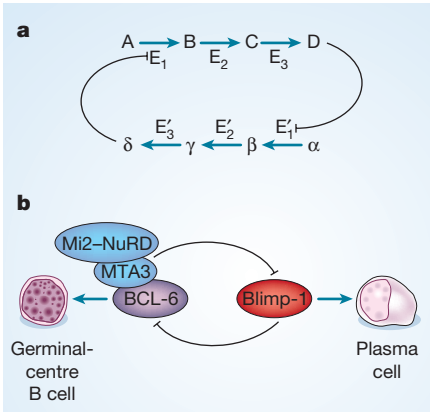

Figure 1 **Double-negative circuits in biology.** a, **In metabolism. Two enzyme pathways are shown. The end-product of one pathway, D, inhibits the other pathway by inhibiting enzyme E′$_1$. Conversely, the end-product of the second pathway, δ, inhibits the first pathway by inhibiting E$_1$. Transient changes in the concentrations of D or δ, perhaps because of changes in environmental conditions, can swing this circuit towards increased production of one end-product or the other. Adapted from ref. 1.** b, **In B-cell differentiation. BCL-6 and Blimp-1 are two gene repressors that inhibit each other's expression. As Fujita *et al.*[2] now show, the MTA3–Mi2–NuRD complex contributes to the repressive activity of BCL-6. BCL-6 is expressed in germinal-centre B cells, Blimp-1 in plasma cells. Transient changes in the expression or activity of either repressor can push a cell towards one or the other differentiation state.**

Cancer

Negative feedback for B cells

Louis M. Staudt

The discovery of a protein that regulates the production of antibody-generating B cells has implications for our understanding of how cancers of the immune system develop — and how they might be treated.

Some 40 years ago, Jacques Monod and François Jacob[1] described the role of double-negative regulatory circuits in biological systems. In their example, two enzyme pathways each yield an end-product that inhibits the activity of the other pathway (Fig. 1a). This circuit has the useful property that a perturbation of one of the regulators, even transiently, can push the system towards one of two cellular states. Although the model was developed by studying microbes, Monod and Jacob envisaged that such circuits would be ideally suited to the differentiation (specialization) of animal cells. Lacking the appropriate experimental tools to test this idea, they noted with some exasperation that "eventually, however, differentiation will have to be studied in differentiated cells". Now, writing in *Cell*, Fujita and colleagues[2] describe a new component of an elegant double-negative circuit that regulates the differentiation of B cells into antibody-secreting plasma cells. Excitingly, their findings might bear on the study and treatment of cancer.

B cells, also known as B lymphocytes, are a crucial weapon in our immune armoury. When these cells meet a particular foreign molecule (antigen), they enter a microenvironment known as the germinal centre in lymphoid organs. There, they divide prolifically and diversify their antigen receptors by a specialized 'hypermutation' mechanism. The process produces some B cells whose receptors have a particularly high affinity for their cognate antigen; these cells are selected for differentiation into plasma cells — the cellular factories that secrete antigen-specific protective antibodies.

A double-negative circuit involving the gene-repressor proteins BCL-6 and Blimp-1 has previously been postulated to regulate this differentiation step[3,4]. BCL-6 is found in germinal-centre B cells, binds to the *Blimp-1* gene, and inhibits its activity[5]. Conversely, the Blimp-1 protein is found in plasma cells, and directly or indirectly represses the *BCL-6* gene, along with virtually every other gene that is expressed only in germinal-centre B cells[3] (Fig. 1b). Blimp-1 also represses the cell-division gene *c-myc*, leading to the proliferation arrest that is characteristic of plasma cells[6]. Inhibiting BCL-6 in cultured germinal-centre B cells 'de-represses' Blimp-1, resulting in differentiation into plasma cells[4]. In germinal centres, strong stimulation of a B cell by its antigen or by activated T cells may transiently decrease BCL-6 expression[7,8], thereby tipping the balance in favour of Blimp-1 expression and differentiation into plasma cells.

Fujita *et al.*[2] now describe an important new component of this regulatory network — the MTA3 protein, a cell-type-specific subunit of a complex called Mi2–NuRD. This complex helps to repress gene expression by influencing the way in which DNA is 'packed' in chromosomes. Somewhat serendipitously, Fujita *et al.* first noted that MTA3 is highly expressed in germinal-centre B cells. They went on to show that it physically associates with BCL-6. It thereby tethers the other Mi2–NuRD subunits to BCL-6 — an association that is essential for BCL-6 to repress its target genes, including *Blimp-1*. From a regulatory standpoint, these results highlight the fact that complexes that modify the packing of DNA can have cell-type-specific subunits that target the complexes to different genes in different cells.

Most unexpectedly, Fujita *et al.* also