Gravity Science from Transponded Interplanetary Laser Ranging

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Abstract

Ranging to passive reflectors on the Moon has delivered frontier science measurements of gravitational theory. Tests of relativistic gravity can be carried orders of magnitude further employing laser ranging to the planets. Ranging to Mercury is discussed as an example: both the science tests that might be reached and the different ways this ranging could be implemented are considered.

Introduction

Two-way laser ranging to orbiting bodies has been proven for a variety of near-Earth spacecraft as well as to the Moon. Ranging to the Moon with passive reflection of the laser photons has brought us to the distance limit at which sufficient returned photons can be obtained back at Earth to produce useful measurements. Nevertheless, this work of the past decades, SLR and LLR, has proven that both laser propagation through the atmosphere and station movements on the flexible and dynamic Earth can be modeled sufficiently well so that detailed information about Newtonian and relativistic gravity can be mapped out through fitting the ranging data with a comprehensive model which includes the gravitational dynamics of bodies and light. Because the Earth and Moon orbits are almost completely under the control of gravity, the 33-year collection of LLR data can be fit to a single orbital arc. Amplitudes of key harmonic terms in the Earth-Moon range are presently fit to a *realistic* precision of a few millimeters, while the key lunar frequencies are measured to 4 parts in 10^{12} or better precision. As a result, LLR today is yielding the most precise constraint on time variation of Newton's gravitational 'constant', $\dot{G}/G \leq 10^{-12}\text{year}^{-1}$; and confirms that Earth and Moon, two celestial bodies of different average chemical composition and containing different fractional amounts of gravitational binding energy as well, yet fall toward the Sun at rates identical to 1.3 parts in 10^{13} [*Williams et al.*, 1996]. These are two of general relativity's strongest experimental confirmations and rejections of alternative theories of gravity. With the new-generation APOLLO ranging program being put together, LLR has the promise to push their gravity science measurements another order of magnitude in the coming years [*Murphy et al.*, 2000].

Some effects of relativistic gravity on orbits of bodies and the propagation of light are even stronger if one looks out to interplanetary ranging in the solar system. Radar ranging to Mercury and Mars and to spacecraft has been underway for decades. The precession of Mercury's perihelion due to relativistic corrections to Newtonian gravity has been well-measured by radar ranging, and both the deflection and retardation of electromagnetic signals due to gravity has found its most precise measurement by radar ranging to planetary and spacecraft targets when those bodies' lines of sight have passed close by the Sun. However, some practical limitations have kept radar ranging from reaching its full theoretical potential. The ranging experiments to Mercury have passively reflected the signals off that planet's surface. Due to topographic variations, limitations on the ranging precision in excess of 100 meters have resulted. When radar signals have passed close by the Sun in key experiments to measure the *Shapiro* gravitational time delay of the signals, large signal dispersion due to the variable solar corona has degraded interpretation of the data, although dual-frequency ranging has substantially helped such experiments by directly employing the frequency-dependence of the corona's index of refraction. Radar ranging to Mars has reached a precision of several meters in range by deploying radar transponders on the Mars surface and on satellites orbiting that planet.

If these now-classic radar ranging missions can be replaced by laser ranging versions of the same, using transponders on or in orbit around other planetary bodies, there appear to be no obstacles to achieve interplanetary ranging precisions comparable to those already achieved in SLR and LLR missions. The modeling challenges are basically the same in SLR, LLR, and interplanetary laser ranging, and the serious coronal modeling problems are eliminated with optical frequency ranging signals. Earth-Mercury laser ranging from a relatively short mission, achieving 5 cm precision in the fit of the planetary orbits, could determine the relativistic perihelion precession (and general relativity's non-linear structure) to a part in 10^5 which is two orders of magnitude beyond present knowledge. Longer missions which combine laser ranging to both Mercury and Mars could reach even an order of magnitude beyond. While such tests of relativistic gravity which result from determining the orbits of bodies can not compete in precision with pure light propagation experiments (see next session), these experiments do probe the important non-linear structure of gravity in a superior way.

The LATOR Mission

Another interesting mission under study is the LATOR (Laser Astrometric Test of Relativity) mission, in which three sides and one angle of a light triangle in the solar system are measured. Two vertices of this triangle are established by spacecraft which are put into orbits which have them transit past the Sun line of sight opposite to Earth. One spacecraft follows the other at about a degree of angular separation. A laser interferometer on the Earth-orbiting space station establishes the third vertex of the triangle. As shown in Figure 1, two-way transponded laser ranging is performed along each of the three sides of the light triangle, while the interferometer measures the triangle's small angle. With interferometer precision of 10^{-13} radians, measurement of the triangle's short side to 1 cm precision and long sides to a slightly less stringent requirement, and location of the light triangle to precision of about 10 meters with respect to the Sun are possible; gravity's key *Eddington parameter* γ can be determined to a precision of 10^{-8}. Within scalar-tensor metric theories of gravity in which a scalar field supplements Einstein's tensor field in establishing relativistic gravity and the corresponding space-time metric, $1-\gamma$ is a measure of the fractional strength of the scalar interaction compared to the dominant tensor interaction. And this parameter affects the coordinate speed of light in presence of a gravitational potential $U(\vec{r}, t)$

$$c(\vec{r}, t) = c \ \left(1 - (1+\gamma)\frac{U(\vec{r}, t)}{c^2}\right)$$

The slowing, globally viewed, of the speed of light near gravitating matter is measured by both the resulting deflection of light rays and the increased time of flight of the rays when passing through the gravitational potentials. LATOR's remarkable ability to measure this key fraction to more than four orders of magnitude higher precision than present knowledge is a result of being able to add to this mission a space-based laser interferometer for measuring a key angle between the light rays.

A plausible scenario has been discussed for why a scalar interaction should be so weak today, even if it were perhaps of more strength and consequence at earlier periods in the history of the universe. If the scalar field's coupling function to matter has a local minimum (attractor point), then the cosmological equations for the background scalar field drives that field's value toward the point of attraction as the universe expands [*Damour and Nordtvedt*, 1993]. And since the strength of the scalar component of gravity is proportional to the square of the slope of the coupling function, the strength of scalar gravity tends to be turned off in this dynamical process. But the process is not complete by this point in time, and estimates of the remnant scalar interaction strength conclude that at least 3 parts in 10^7 of the solar system's gravity today should still result from the scalar interaction, i.e., $1-\gamma \geq 3\ 10^{-7}$. LATOR has a good chance to either detect this remnant interaction or rule out this entire scenario of alternative theories! Measuring the relativistic gravity parameter g has broad significance for the entire structure of this interaction. It can be shown that all the structure parameters of the gravitational interaction at all orders of perturbation theory collapse to their general relativistic values as γ approaches its pure tensor gravity value of one. The value of g is the key portal into the full structure of gravity!

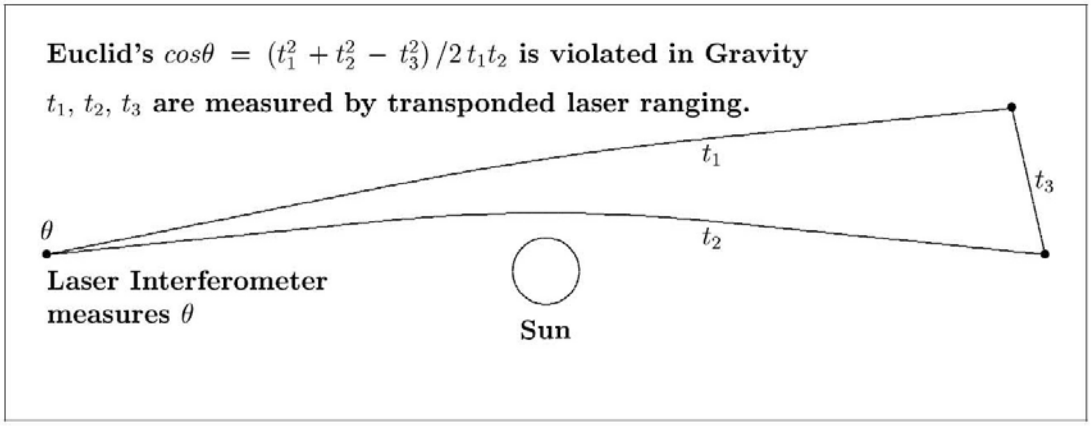

Figure 1. The three sides of a light triangle are each measured by two-way, transponded laser ranging, while the triangle's small angle is measured by a laser interferometer. The combination of these four measured quantities, over-determined if Euclidean geometry held, determines the deflection of the light rays by the Sun's gravity.

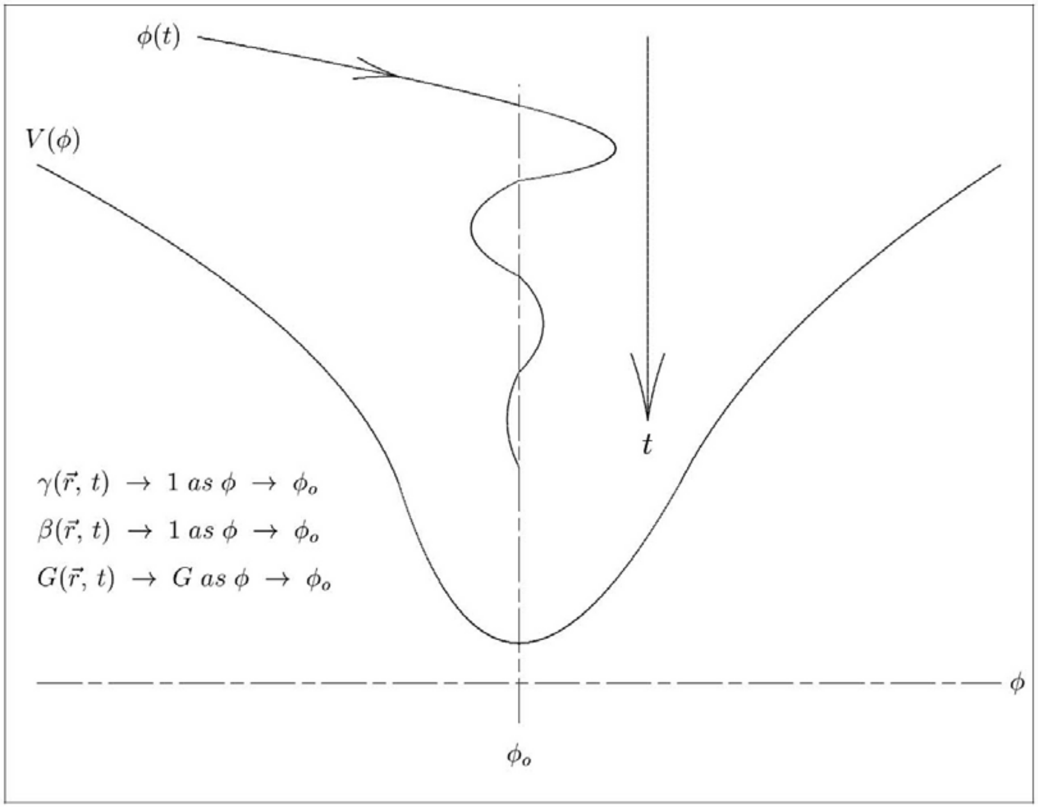

Figure 2. Typical cosmological dynamics of a background scalar field $\phi(t)$ is shown if that field's coupling function $V(\phi)$ has an attracting point ϕ_O. The strength of the scalar interaction's coupling to matter is proportional to the square of the coupling function's derivative and therefore weakens as the attracting point is approached. In scalar-tensor metric theory, for example, the Eddington parameter γ and non-linearity parameter β both approach the values of one, Newton's G loses any space-time variation, and gravity asymptotically becomes a pure tensor interaction.

References

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