Relativity and Fundamental Physics

Sergei Kopeikin (1,2,*)

1) ***Dept. of Physics and Astronomy, University of Missouri, 322 Physics Building., Columbia, MO 65211, USA***
2) ***Siberian State University of Geosystems and Technology, Plakhotny Street 10, Novosibirsk 630108, Russia***

Abstract

Laser ranging has had a long and significant role in testing general relativity and it continues to make advance in this field. It is important to understand the relation of the laser ranging to other branches of fundamental gravitational physics and their mutual interaction. The talk overviews the basic theoretical principles underlying experimental tests of general relativity and the recent major achievements in this field.

Introduction

Modern theory of fundamental interactions relies heavily upon two strong pillars both created by Albert Einstein – special and general theory of relativity. Special relativity is a cornerstone of elementary particle physics and the quantum field theory while general relativity is a metric-based theory of gravitational field. Understanding the nature of the fundamental physical interactions and their hierarchic structure is the ultimate goal of theoretical and experimental physics. Among the four known fundamental interactions the most important but least understood is the gravitational interaction due to its weakness in the solar system – a primary experimental laboratory of gravitational physicists for several hundred years.

Nowadays, general relativity is a canonical theory of gravity used by astrophysicists to study the black holes and astrophysical phenomena in the early universe. General relativity is a beautiful theoretical achievement but it is only a classic approximation to deeper fundamental nature of gravity. Any possible deviation from general relativity can be a clue to new physics (Turyshev, 2015). Therefore, the basic principles of general relativity are under continuous scrutiny exploration in all possible regimes characterizing by the strength of gravitational field. Until recently, testing of general relativity was carried out mostly by observing orbital and rotational motion of celestial bodies in optics or with radio waves (Kopeikin, Efroimsky, & Kaplan, 2011). The motions of the bodies and propagation of light/radio waves are described by mathematical solutions of their equations of motion which, in their own turn, depend parametrically on the gravitational potentials of a particular gravity field theory. The mathematical model of motion

---

[*] E-mail: kopeikins@missour.edu

fits to observational data to determine the various parameters characterizing the model of matter and the structure of spacetime.

Most of the fitting parameters have no fundamental significance and depend on the choice of coordinates. On the other hand, the fundamental parameters stay invariant (keep the same numerical value) under the change of a computational algorithm, coordinates and the gauge conditions imposed on the gravitational potentials. Moreover, their measured values converge to a unique limit as the number of observations (normal points) increases. Examples of the fundamental parameters are the fundamental ultimate speed *c,* the universal gravitational constant *G,* parameters β and γ of a scalar-tensor theory of gravity, parameters of the standard model extension, etc. Measuring the fundamental parameters of the gravity theory is a primary goal of experimental gravitational physics.

For a long time the best model used by experimentalists for testing general relativity was the parametrized post-Newtonian (PPN) formalism (Will, 2014). This formalism assumes that a gravitating system under exploration like the solar system, a binary pulsar, etc., is isolated from the rest of the universe and can be covered by a global coordinate system, x^μ, extending up to infinity where the spacetime is assumed to be asymptotically-flat[†]. The PPN formalism operates with the metric tensor $g_{\mu\nu}$ that is assumed to be a solution of some alternative theory of gravity characterized by ten PPN parameters $\beta, \gamma, \xi, \alpha_1, \alpha_2, \alpha_3, \zeta_1, \zeta_2, \zeta_3, \zeta_4$ taking particular numerical values, for example, in general relativity $\beta = \gamma = 1,$ and all other PPN parameters are nil. Scrutiny theoretical analysis of the PPN formalism reveals that it does not have sufficient flexibility and rigor to respond adequately to the growing precision of astronomical observations, and must be used with forethought when implementing for physical interpretation of the results of relativistic experiments.

A bona fide approach to theoretical modelling of relativistic experiments is based on introducing of a parametrized Lagrangian of the gravity theory which includes besides the metric tensor the alternative long-range fields (scalar, vector, and tensor) that can be potentially responsible for possible violations of general relativity. This approach has been proposed by Alan Kostelecky and is known as the standard model extension or SME (Colladay, 2015). Lagrangian of the SME can be schematically written down as follows

$$L = L_E(g_{\mu\nu}, g_{\mu\nu,\sigma}, g_{\mu\nu,\sigma\rho}) + L_M(g_{\mu\nu}, \phi_b, \phi_{b;\mu}) + L_I(g_{\mu\nu}, \phi_b, \phi_{b;\mu}, \psi_c, \psi_{c;\mu}) \ , \quad (1)$$

where L_E is the Hilbert-Einstein gravitational Lagrangian, depending on the metric tensor and its first and second derivatives, L_M is the Lagrangian of the matter fields ϕ_b and its covariant derivatives $\phi_{b;\mu}$, and L_I is the Lagrangian of interaction between the matter fields and gravity which also includes the gauge fields ψ_c and their covariant derivatives $\psi_{c;\mu}$ [‡].

Equations of the gravitational field as well as equations of motion of the matter and gauge fields are derived from the parameterized Lagrangian (1) by taking the variational derivatives with respect to corresponding dynamic variables (Petrov et al., 2017). Equations of motion of massive

---

[†] The spacetime Greek indices $\mu, \nu, \sigma,$ etc. take values 0,1,2,3.

[‡] The small Roman indices *b,c,* etc. characterize the nature of the matter fields and can numerate the fields themselves, be tensor indices or multi-indices of a gauge theory, etc. The covariant derivatives with respect to the metric tensor $g_{\mu\nu}$ are denoted with a semicolon with a Greek index after it. Partial derivatives with respect to coordinates are denoted with a comma with a Greek index after it.

gravitating bodies are derived either from macroscopic equations of motion of matter comprising the extended bodies or by making use of the method of asymptotic matching of gravitational fields for compact astrophysical objects like black holes or neutron stars (Kopeikin, 2014).

Currently, there are several hierarchic levels of relativistic experiments for testing general relativity and fundamental physics. They include weak-field tests in

- laboratory (torsion balance, atomic clocks, LHC, etc.),
- Earth-Moon system (GNSS, GPB, SLR, LLR),
- the solar system (deep-space spacecraft tracking, astrometry, VLBI, interplanetary ranging),

and strong-field tests in/with

- binary/double pulsars (strong field tests: pulsar timing),
- gravitational waves (strong-field tests: LIGO, VIRGO, PTA),
- cosmology (strong-field tests: COBE, PLANCK, SKA, etc.).

Gravitational Waves and Binary Pulsars

The most comprehensive and precise test of general relativity completed so far, is with the binary pulsar PSR 1913+16 which was discovered in 1974 by Joe Taylor and Russel Hulse. The binary pulsar consists of two neutron stars with masses 1.438 and 1.390 solar masses. It has the orbital period $P_b = 0.3229974489$ d, with a projected semi-major axis of the orbit, $x = \frac{a \sin i}{c} = 2.34177$ s, and eccentricity $e = 0.617134$. This configuration makes the binary pulsar one of the most relativistic objects in our galaxy allowing us to confirm validity of general relativity with precision 0.16% through measurement of an impressive number of relativistic parameters including the quadratic Doppler effects, the gravitational red shift, the anomalous precession of the periastron, the Shapiro gravitational time delay, the decay of the orbital period of the system due to the emission of gravitational waves, and many more (Weisberg & Huang, 2016; Wex, 2014). Relativistic theory of motion of the binary pulsars had been developed by a number of authors and it has been used to calculate a library of the templates of gravitational waves from the coalescing binary black holes which finally culminated in the direct detection of the gravitational waves by LIGO detectors on September 14, 2015 (Abbott, B.P. et al, 2016). This discovery opens a new epoch in experimental gravitational physics as gravitational waves can propagate at huge distances without extinction in interstellar/intergalactic medium and bring us information about physical processes at extremely large (Planck) densities of matter just before formation of black holes or in the very early universe.

Besides gravitational waves and binary pulsars we have rich technical possibilities to test the foundations of special and general relativity within the solar system. Below we discuss a few experiments having been performed recently.

Relativistic Time Metrology

Time is the most mysterious substance in the universe. Besides of its enigmatic origin and numerous paradoxes we are struggling with its precise measurement with clocks. The essence of the problem is that the time as a mathematical concept and the time measured by clocks can differ even in case when the clocks are ideal. Indeed, in order to measure time, general relativity suggests using the, so-called, optical clocks which consists of two mirrors at a fixed distance and a light ray (photon) bouncing between them. The number of bounces can be counted and used as a time scale. In practice, this type of clock is realized as an optical cavity resonator. Atomic clocks using transitions between various levels of energy in a single atom (ion) are operating on the principles of quantum mechanics which involves additional hypothesis. The two clocks will read out the same time, if and only if, general relativity and quantum mechanics are fundamentally compatible. Therefore, simple experiment of comparison of the rate of two clocks on a sufficiently long time interval can already tell us a lot about the fundamental physics. Such an experiment has been recently performed in the Düsseldorf University (Wiens, Nevsky, & Schiller, 2017) to investigate a hypothetical differential effect of the universe's expansion on rulers and atomic clocks (Kopeikin, 2014), to constrain a hypothetical violation of the principle of Local Position Invariance for resonator-based clocks and to derive bounds for the strength of space-time fluctuations. The clocks were monitored over 163-day interval but no mean fractional drift magnitude was found at the level less than 1.4×10^{-20}/s. This demonstrates a full compatibility of the quantum mechanics and general relativity at the significantly improved experimental limit by the means of the time metrology.

Gravitomagnetic Field Measurement

General relativity is fundamentally different from the Newtonian theory of gravity which operates only with gravitational fields that are produced by instantaneous distribution of masses. This type of gravitational field is called gravitoelectric by a formal analogy with the Coulomb electrostatic law. General relativity admits existence of gravitational fields which are produced by mass currents, and this type of gravitational field is called gravitomagnetic by a formal analogy with the Faraday and Ørsted laws of electromagnetism. Measurement of gravitomagnetic field is a challenging task for experimenters as the magnitude of the field is extremely small within the solar system.

Gravitomagnetic field can be generated by two types of mass current – rotational and translational (Ciufolini & Wheeler, 1995). The gravitomagnetic fields corresponding to these types of the current are called *intrinsic* and *extrinsic* respectively (Kopeikin & Fomalont, 2007). Any type of gravitomagnetic field causes a relativistic effect called dragging of a local inertial frame. In case of the intrinsic gravitomagnetic field this effects is also known under the name of the Lense-Thirring precession and Schiff precession. The difference between the two precessions is that the Lense-Thirring precession is related to the precession of the orbital plane of a test body orbiting a massive rotating body while the Schiff precession is related to the precession of a spin of a gyroscope placed to the gravitomagnetic field of this body. In terms of the Hamiltonian mechanics the Lense-Thirring precession is due to the spin-orbit coupling effect while the Schiff precession is due to the spin-spin coupling. It is remarkable that the two precessions have been recently measured with the precision being enough to speak about the confirmation of the existence of the intrinsic gravitomagnetic field validating this important aspect of general relativity.

The Lense-Thirring precession has been verified by the laser ranging technique applied to geodetic satellites LAGEOS and LARES with the precision better than 10% by the team led by Ignazio Ciufolini (Ciufolini & Pavlis, 2004; Ciufolini, et al., 2016) – the most recent test is based on the model GGM05S of the Earth's gravitational field derived from the results of the space geodesy GRACE mission. The Schiff precession has been confirmed in a dedicated Gravity Probe B (GP-B) experiment (Everitt, et al., 2011) with a precision about 20%.

Method of measuring the *extrinsic* gravitomagnetic field is different as it requires detecting the frame dragging effect caused by the translational motion of a massive body which is not accumulated over time in contrast to the Lense-Thirring or Schiff precession. The idea of measuring the extrinsic gravitomagnetic field has been proposed in our article (Kopeikin, 2001) where we had shown that the finite speed of gravity affects very-long baseline interferometric observations of quasars during the time of their line-of-sight close angular encounter with a massive body (Jupiter, Saturn). The gravitomagnetic field vanishes in the Newtonian theory where the speed of gravity is infinite. Therefore, measuring the effect caused by the finite speed of gravity is equivalent to measuring the gravitomagnetic field (Kopeikin, 2006). The Lense-Thirring and Schiff precessions caused by the intrinsic gravitomagnetic field depend on the finite value of the speed of gravity as well. However, the speed of gravity couples with the rotational velocity of matter in the stationary part of the g_{0i} component of the metric tensor (Will, 2014) while the speed of gravity associated with the extrinsic gravitomagnetic field couples with (normalizes) the time derivatives of the metric tensor, and can be measured only in case of time-dependent gravitational field (Kopeikin S., 2004). We noticed (Kopeikin, 2001) that while a radio wave from a quasar propagates through gravitational field of Jupiter, it does not remain static as Jupiter moves around the barycenter of the solar system. This orbital motion of Jupiter must be taken into account in calculation of the gravitational Shapiro time delay of the wave by Jupiter. The translational gravitomagnetic field of Jupiter drags the local inertial frame along Jupiter's orbit and reveals as a tiny excess to the static part of the Shapiro time delay. We have determined the relativistic light deflection of the quasar J0842+1835 as Jupiter passed within 3.7° on September 8, 2002 by measuring the time delay using the Very Long Baseline Array (VLBA) and Effelsberg radio telescopes at 8.4 GHz (Fomalont & Kopeikin, 2003). At closest approach, general relativity predicts a radial (static) deflection of 1190 μas and a tangential (gravitomagnetic) deflection in the direction of Jupiter's motion of 51 μas. Our experiment achieved an rms position error of ≤ 10 μas and measured the gravitomagnetic deflection with rms error ≤ 20% as predicted by general relativity. The increased positional accuracy for this VLBI phase-referencing experiment was achieved by using two calibrator sources. We repeated the measurement of the extrinsic gravitomagnetic field in a series of VLBI experiments with Jupiter and Saturn (Fomalont et al., 2009). The results validate the existence of the gravitomagnetic field and are consistent with the prediction of general relativity.

Acknowledgement

This work has been supported by the Grant No. 14-27-00068 of the Russian Science Foundation.

Bibliography

Abbott, B.P. et al. (2016). GW150914: First results from the search for binary black hole coalescence with Advanced LIGO. *Physical Review D*, vol. 93, issue 12, id.122003.

Ciufolini, C., & Pavlis, E. (2004). A confirmation of the general relativistic prediction of the Lense-Thirring effect. *Nature, 431*(7011), 958-960.

Ciufolini, I., & Wheeler, J. (1995). *Gravitation and Inertia.* Princeton: Princeton University Press.

Ciufolini, I., Paolozzi, A., Pavlis, E., Koenig, R., Ries, J., Gurzadyan, V., et al. (2016). A test of general relativity using the LARES and LAGEOS satellites and a GRACE Earth gravity model. Measurement of Earth's dragging of inertial frames. *European Physical Journal C, 76*, 120.

Colladay, D. (2015, June 12-18). *The minimal Standard Model Extension*. Retrieved January 13, 2017, from Second IUCSS Summer School on the Lorentz- and CPT-violating Standard-Model Extension: http://www.indiana.edu/~lorentz/sme2015/Colladay1.pdf

Everitt, C. W., Debra, D. B., Parkinson, B., Turneaure, J., Conklin, J., Heifetz, M., et al. (2011). Gravity Probe B: Final Results of a Space Experiment to Test General Relativity. *Physical Review Letters, 106*(22), id. 221101.

Fomalont, E., & Kopeikin, S. (2003). The Measurement of the Light Deflection from Jupiter: Experimental Results. *The Astrophysical Journal, 598*(1), 704-711.

Fomalont, E., Kopeikin, S., Jones, D., Honma, M., & Titov, O. (2009). Recent VLBA/VERA/IVS tests of general relativity. In S. Klioner, P. Seidelmann, & M. Soffel (Ed.), *Relativity in Fundamental Astronomy: Dynamics, Reference Frames, and Data Analysis. Proceedings of the International Astronomical Union, IAU Symposium*, *261*, pp. 291-295. Virginia Beach.

Kopeikin, S. (2001). Testing the Relativistic Effect of the Propagation of Gravity by Very Long Baseline Interferometry. *The Astrophysical Journal Letters, 556*(1), 1-5.

Kopeikin, S. (2004). The speed of gravity in general relativity and theoretical interpretation of the Jovian deflection experiment. *Classical and Quantum Gravity, 21*(13), 3251-3286.

Kopeikin, S. (2006). Gravitomagnetism and the Speed of Gravity. *International Journal of Modern Physics D, 15*(3), 305-320.

Kopeikin, S. (2014). *Frontiers in Relativistic Celestial Mechanics* (Vol. 1). (S. Kopeikin, Ed.) Berlin: De Gruyter.

Kopeikin, S. (2014). Optical cavity resonator in an expanding universe. *General Relativity and Gravitation, 47*, id.5, 18 pp.

Kopeikin, S., & Fomalont, E. (2007). Gravimagnetism, causality, and aberration of gravity in the gravitational light-ray deflection experiments. *General Relativity and Gravitation, 39*(10), 1583-1624.

Kopeikin, S., Efroimsky, M., & Kaplan, G. (2011). *Relativistic Celestial Mechanics of the Solar System.* Berlin: Wiley-VCH.

Petrov, A., Kopeikin, S., Lompay, R., & Tekin, B. (2017). *Metric theories of gravity: Perturbations and conservation laws.* Berlin: De Gruyter.

Turyshev, V. (2015). Space-based Tests of Relativistic Gravitation. In R. Peron, M. Colpi, V. Gorini, & U. Moschella (Eds.), *Gravity. Where do we stand?* (pp. 211-233). Switzerland: Springer International Publishing.

Weisberg, J., & Huang, Y. (2016). Relativistic Measurements from Timing the Binary Pulsar PSR B1913+16. *The Astrophysical Journal*, vol. 829, issue 1, id. 55.

Wex, N. (2014). Testing Relativistic Gravity with Radio Pulsars. In S. M. Kopeikin (Ed.), *Frontiers in Relativistic Celestial Mechanics* (Vol. 2). Berlin: De Gruyter.

Wiens, E., Nevsky, A., & Schiller, S. (2017). Resonator with ultra-high length stability as a probe for Equivalence-Principle-violating physics. *Physical Review Letters , in press (e-print https://arxiv.org/abs/1612.01467)*.

Will, C. (2014). The Confrontation between General Relativity and Experiment. *Living Reviews in Relativity, 17*(1), id. 4, 117 pp.