Spacetime structure exploration plan in the earth-moon system

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1. SCAS, Gyposcope, and Spacetime structure exploration
2. Potenial, Curvature and gravitational wave detection in the earth-moon system
3. Geometrodynamic field moment Measurement
4. From the CPT violation to Lorentz Invariance Violation: Gravitional 2nd Redshift and LT precession

SCAS and Gyposcope

- Space cold atomic clock (SCAC): Tests of Cold Atom Clock in Orbit [Liu et al. , 2017]. ACES in ISS. An Atomic Clock with 10^{-18} Instability on the ground [Hinkley et al. , 2013].
- Optical clock: Frequency Comparison of Two High-Accuracy Al^{+} Optical Clocks [Chou et al. , 2010a].
- Gyposcope: Continuous Cold-Atom Inertial Sensor with 1 nrad/sec Rotation Stability [Dutta et al. , 2016].
- Clocks and Relativity: optical clocks is enough to measure relativity [Chou et al. , 2010b], many relativistic experiments with atomic clocks has been proposed [Reynaud et al. , 2009], A precision measurement of the gravitational red-shift by the interference of matter waves has been done by Müller et al. [2010], even a clock can directly linking time to a particle's mass [Lan et al. , 2013].

Relativitic geodesic

- Relativitic geodesic: geodesic based on relativitic effect.
- A Spaceborne Gravity Gradiometer Concept Based on Cold Atom Interferometers for Measuring Earth's Gravity Field [Carraz et al. , 2014].
- High Performance Clocks and Gravity Field Determination [Müller et al. , 2018], Atomic Clocks for Geodesy [Mehlstäubler et al. , 2018].

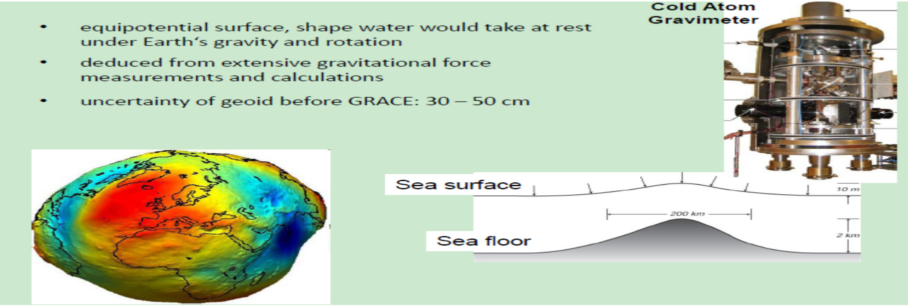


Figure: The slide from Christian Lisdat, Transportable optical clocks, Fundamental Physics in Space, 656 th WE Heraeus Seminar, October 23 – 27, 2017.

Psedo-Newtonian potenial in Kerr Spacetime and Local quasi-inertial frame of PPN

- Our plan is that spacetime structure exploration in the earth-moon system by the above mentioned thecniques, which focus on surveying the gravitational potential and gravitational first order redshift in Schwarzchild spacetime geometry of the earth-moon system.
- Psedo-Newtonian potenial in Kerr Spacetime: one example-Paczyński-Wiita potential, Abramowicz [2009] A step-by-step "derivation". Commentary on Paczyńsky & Wiita [1980]. Although all Psedo-Newtonian potenial can back to PPN (Parameterized Post-Newtonian formalism) in some order, we will check it in the experiment.
- Local quasi-inertial frame of PPN: we also will check the effectness of the diffecence local quasi-inertial frame defined of PPN in the experiment.

Clock and Gyposcope as the porbe of curvature

- The curvature have many structure, and very small. Kretschmann scalar for the curvature $\xi = \left(\mathrm{R}^{\alpha\beta\gamma\delta}\mathrm{R}_{\alpha\beta\gamma\delta}\right)^{1/2} = \sqrt{48}\,\frac{\mathrm{GM}}{\mathrm{r}^3\mathrm{c}^2}$ in Schwarzschild metric [Baker et al. , 2015], the early paper estimate the curvature is simliar but less $\sqrt{48}$ in Psaltis [2008], the early paper use Kretschmann scalar to estimate curvature in [Henry, 2000].
- Sachs & Wu [1977] predict the clock Synchronization rate changing with the curvature by h^{-1}.
- Gyposcope and Riemann tensor: Audretsch & Lämmerzahl [1983] had study Local and nonlocal measurements of the Riemann tensor.

Gravitational wave detection in 3 LPs

- With the technology development in the clock which include cold atomic interferometric and optical frequency comb et al., and in the gyposcope which include laser gyroscopes and fiber optic gyroscopes based on the Sagnac effect and the matter wave gyroscopes et al., the plan of Atomic Gravitational wave Interferometric Sensor (AGIS) was proposed.
- If had high precision instrumenmts in 3 satellites at least, we will done detection of gravitational waves like AGIS.
- A comparison between matter wave and light wave interferometers for the detection of gravitational waves [Delva et al. , 2006].

Space Curvature Precession in the Quasi-Stationary Curved spacetime: Predictd by Geometrodynamic field moment

and One co-product of Curvature in the frame of Gravitoelectromagnetism

- Gravitoelectromagnetis refers to a set of formal analogies between the equations for electromagnetism and relativistic gravitation; specifically: between Maxwell's field equations and an approximation, valid under certain conditions, to the Einstein field equations for general relativity.
- In the Slow rotation of spacetime, Geometrodynamic field moment should been Measured.
- Space Curvature Precession is which Quantified Predicted by Jantzen et al. [1992] based on GEM.
- We will try to find it in the data of the clock and the gyposcope.
- B1259–63 [Shannon et al. , 2014]. Pros: We have 3 sources (15-30 M main-sequence stellar and 1.4 M pulsar) in the sky.
- Cons: The rotation of MMSS is slow that lead to the Schwarzschild spacetime geometry is enough. Pulsar is not MSP (milli-second pulsar).
- From the experiment, After Riemann Curvature Tensor Measurement in the Quasi-Stationary spacetime of the periapsis from descending node to ascending node.

Exercise 40.8. SPIN-CURVATURE COUPLING

Consider a spinning body (e.g., the Earth or a gyroscope or an electron) moving through curved spacetime. Tidal gravitational forces produced by the curvature of spacetime act on the elementary pieces of the spinning body. These forces should depend not only on the positions of the pieces relative to the center of the object, but also on their relative velocities. Moreover the spin of the body [illegible] in a comoving orthonormal frame. is a measure of the relative positions and velocities of its pieces. Therefore one expects the spin to couple to the tidal gravitational forces—i.e., to the curvature of spacetime—producing

Figure: The early study in Misner et al. [1973].

§40.8. IS THE GRAVITATIONAL CONSTANT CONSTANT? 1121

deviations from geodesic motion. Careful solution of the PPN equations of Chapter 39 for general relativity reveals [Papapetrou (1951), Pirani (1956)] that such coupling occurs and causes a deviation of the worldline from the course that it would otherwise take; thus,

$$m\frac{Du^\alpha}{d\tau} = -S_\mu u_\nu \frac{D^2 u_\beta}{d\tau^2}\epsilon^{\alpha\mu\nu\beta} + \frac{1}{2}(\epsilon^{\lambda\mu\rho\tau}R^{\alpha\sigma}{}_{\lambda\mu})u_\sigma S_\rho u_\tau. \quad (40.39)$$

Evaluate, in order of magnitude, the effects of the supplementary term on planetary orbits in the solar system.

[*Answer:* They are much too small to be detected. However, there are two other material places to look for the effect: (1) when a rapidly spinning neutron star, or a black hole endowed with substantial angular momentum enters the powerful tidal field of another neutron star or black hole; and (2) when an individual electron, or the totality of electrons in the "Dirac

Another co-product of Curvature in the frame of Gravitoelectromagnetism:

Gravitomagnetic clock in the Quasi-Stationary Curved spacetime

- Cohen & Mashhoon [1993] give the gravitomagnetic clock effect for the circular orbits. Recently, generalized gravitomagnetic clock effect was calculated for the GNSS near the earth[Hackmann & Lämmerzahl, 2014].
- We will try to find it in the data of the clock and the gyposcope.
- B1259−63 Shannon et al. [2014]

Riemann Curvature Tensor Measurement in the Quasi-Stationary strong curved spacetime

- We will try to have Riemann Curvature Tensor Measurement in the Quasi-Stationary spacetime of the periapsis from descending node to ascending node.
- From the theory, the estimated from Schwarzschild metric or Kerr metric, even the Solutions of Einstein field equations in cylindrical coordinate system, EOB(Effective One Body) model...
- We will try to find it in the data of the clock and the gyposcope.
- From the experiment, have the best RMS of timing after considered the coordinate time, the coordinate length, the coordinate mass, Lense-Thirring Precession, Gravitational secondary Red-shift...

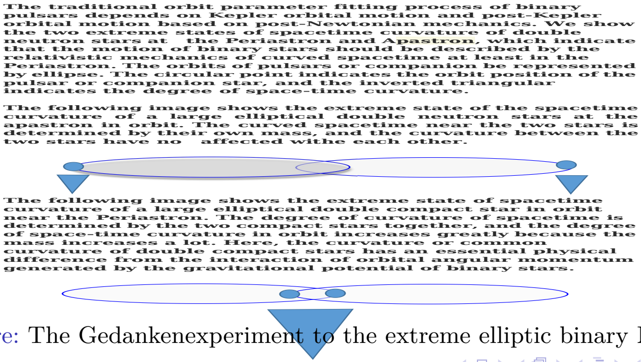
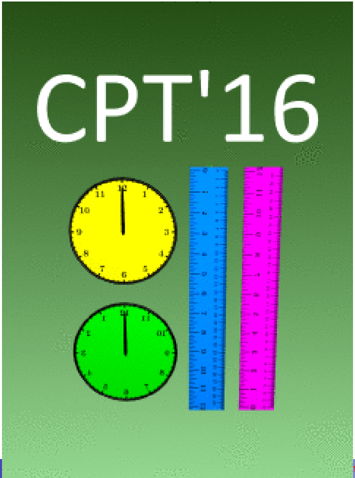


Figure: The Gedankenexperiment to the extreme elliptic binary MSP.

From the CPT violation to Lorentz Invariance Violation

- The symmetry is the important concept in the physics[Noether, 1918], the discovery of parity conservation violations in weak interactions make physicist pay attention to CPT conservation in the particle physics and high energy physics[Lee & Yang, 1956]. After Yang-Mills used gauge invariance to the particle physics[Yang & Mills, 1954], the symmetry and symmetry violations have the more impact on the standard model which based on the gauge theory and Yang-Mills field.
- After Colladay & Kostelecký [1998] give the theory about Lorentz-violating extension of the standard model, the relation in the gravity, Lorentz violation, and the standard model also been discussed[Kostelecký, 2004].
- Then, Greenberg [2002] point out that CPT violation implies violation of Lorentz invariance.



Gravitional 2nd Redshift of CPT violation

- The time dilation symmetry violations in the Gravitational secondary Red-shift:
- After Pound & Rebka [1960] measure the gravitational first order red-shift, Jaffe & Vessot [1974] want to study the Second-Order Gravitational Redshift in the earth[Jaffe & Vessot, 1975].
- Then Krisher [1993] point out that the symmetry violations is exist in the parametrized post-Newtonian gravitational redshift. Yuan-Hong & Jun-Li [2011] also have the similar result from the frame of gravitoelectromagnetism.
- We will try to find it in the data of the clock and the gyposcope.

LT precession of CPT violation

- In 1687, Newton [1687] published his book which include the famous discusson of inertial forces on a fiuid contained in a rotating vessel. This discussion was critically re-examined by Mach [1893] in an attempt to understand better how inertial forces arise. He suggested that the shape of the water-surface may depend on the rotation of the vessel “if the sides of the vessel increased in thickness and mass till they were ultimately several leagues thick”.
- A calculation of such effects became possible afetr Einstein [1915] formulated his general theory of relativity. Lense & Thirring [1918] proposes the precession on the vertical direction of the motion.Lense-Thirring Precession (i.e. Frame dragging) aways was find in the Astrophysical Context[Stella & Possenti, 2009], and in Physics as gravitomagnetism effect[Schäfer, 2009].
- Recently, He & Wang [2006] study frame dragging in the field of Kerr spacetime which based on the model of rotating dust cloud in general relativity[Bonnor, 1977, Steadman, 1999]. Dubey & Sen [2016] also study frame-dragging from charged rotating body.
- Those result show that the LT precession depend on the azimuthal, and the latitude, and the mass of the central massive body (i.e. orbital symmetry violation).
- As O’Connell [2009] point out that LT effect of one body is the difference with two body, we think the above gyroscope model in the curve spacetime is the better than the two spin particle model for understand one body LT effect near the periapsis.
- We will try to find it in the data of the clock and the gyposcope.

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  We Just show the plan.
- Courtesy of WIKI et al.

Abramowicz, M. A. 2009. The Paczyński-Wiita potential. A step-by-step "derivation". Commentary on: Paczyński B. and Wiita P. J., 1980, AA, 88, 23. Astronomy Astrophysics, 500(1), 213–214.

Audretsch, Jürgen, & Lämmerzahl, Claus. 1983. Local and nonlocal measurements of the Riemann tensor. General Relativity Gravitation, 15(6), 495–510.

Baker, T., Psaltis, D., & Skordis, C. 2015. Linking Tests of Gravity on All Scales: from the Strong-field Regime to Cosmology. ApJ, 802(Mar.), 63.

Bonnor, W. B. 1977. A rotating dust cloud in general relativity. Journal of Physics A Mathematical General, 10(Oct.), 1673–1677.

Carraz, O., Siemes, C., Massotti, L., Haagmans, R., & Silvestrin, P. 2014. A Spaceborne Gravity Gradiometer Concept Based on Cold Atom Interferometers for Measuring Earth's Gravity Field. Microgravity Science and Technology, 26(Oct.), 139–145.

Chou, C. W., Hume, D. B., Koelemeij, J. C. J., Wineland, D. J., & Rosenband, T. 2010a. Frequency Comparison of Two High-Accuracy Al^+ Optical Clocks. Physical Review Letters, 104(7), 070802.

Chou, C. W., Hume, D. B., Rosenband, T., & Wineland, D. J. 2010b. Optical Clocks and Relativity. Science, 329(Sept.), 1630.

Cohen, J. M., & Mashhoon, B. 1993. Standard clocks, interferometry, and gravitomagnetism. Physics Letters A, 181(Oct.), 353–358.

Colladay, D., & Kostelecký, V. A. 1998. Lorentz-violating extension of the standard model. Phys. Rev. D, 58(11), 116002.

Delva, P., Angonin, M. C., & Tourrenc, P. 2006. A comparison between matter wave and light wave interferometers for the detection of gravitational waves. Physics Letters A, 357(4–5), 249–254.

Dubey, A. K., & Sen, A. K. 2016 (Oct.). Frame-dragging from charged rotating body. Page 012065 of: Journal of Physics Conference Series. Journal of Physics Conference Series, vol. 759.

Dutta, I., Savoie, D., Fang, B., Venon, B., Alzar, C. L. Garrido, Geiger, R., & Landragin, A. 2016. Continuous Cold-Atom Inertial Sensor with 1 nrad/sec Rotation Stability. Phys.rev.lett, 116(18), 183003.

Einstein, A. 1915. Die Feldgleichungen der Gravitation. Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), Seite 844-847.

Greenberg, O. W. 2002. CPT Violation Implies Violation of Lorentz Invariance. Physical Review Letters, 89(23), 231602.

Hackmann, E., & Lämmerzahl, C. 2014. Generalized gravitomagnetic clock effect. Phys. Rev. D, 90(4), 044059.

He, T.-M., & Wang, Y.-J. 2006. Frame dragging in the field of Kerr family. Chinese Physics, 15(Jan.), 232–234.

Henry, R. C. 2000. Kretschmann Scalar for a Kerr-Newman Black Hole. ApJ, 535(May), 350–353.

Hinkley, N., Sherman, J. A., Phillips, N. B., Schioppo, M., Lemke, N. D., Beloy, K., Pizzocaro, M., Oates, C. W., & Ludlow, A. D. 2013. An Atomic Clock with 10^{-18} Instability. Science, 341(Sept.), 1215–1218.

Jaffe, J., & Vessot, R. F. C. 1974 (Mar.). The Second-Order Gravitational Redshift. Page 279 of: Bulletin of the American Astronomical Society. BAAS, vol. 6.

Jaffe, J., & Vessot, R. F. C. 1975. The second-order gravitational redshift. General Relativity and Gravitation, 6(Feb.), 55–61.

Jantzen, R. T., Carini, P., & Bini, D. 1992. The many faces of gravitoelectromagnetism. Annals of Physics, 215(Apr.), 1–50.

Kostelecký, V. A. 2004. Gravity, Lorentz violation, and the standard model. Phys. Rev. D, 69(10), 105009.

Krisher, T. P. 1993. Parametrized post-Newtonian gravitational redshift. Phys. Rev. D, 48(Nov.), 4639–4644.

Lan, S.-Y., Kuan, P.-C., Estey, B., English, D., Brown, J. M., Hohensee, M. A., & Müller, H. 2013. A Clock Directly Linking Time to a Particle's Mass. Science, 339(Feb.), 554.

Lee, T. D., & Yang, C. N. 1956. Question of Parity Conservation in Weak Interactions. Physical Review, 104(Oct.), 254–258.

Lense, J., & Thirring, H. 1918. Über den Einfluß der Eigenrotation der Zentralkörper auf die Bewegung der Planeten und Monde nach der Einsteinschen Gravitationstheorie. Physikalische Zeitschrift, 19.

Liu, L., Lü, D., Chen, W., Li, T., Qu, Q., Wang, B., Li, L., Ren, W., Dong, Z., Zhao, J., Xia, W., Zhao, X., Ji, J., Ye, M., Sun, Y., Yao, Y., Song, D., Liang, Z., Hu, S., Yu, D., Hou, X., Shi, W., Zang, H., Xiang, J., Peng, X., & Wang, Y. 2017. Tests of Cold Atom Clock in Orbit. ArXiv e-prints, Sept.

Mach, E. 1893. The science of mechanics: A critical and historical account of its development.

Mehlstäubler, T., Grosche, G., Lisdat, C., Schmidt, P., & Denker, H. 2018. Atomic Clocks for Geodesy. ArXiv e-prints, Mar.

Misner, C. W., Thorne, K. S., & Wheeler, J. A. 1973. Gravitation.

Müller, H., Peters, A., & Chu, S. 2010. A precision measurement of the gravitational redshift by the interference of matter waves. Nature, 463(Feb.), 926–929.

Müller, J., Dirkx, D., Kopeikin, S. M., Lion, G., Panet, I., Petit, G., & Visser, P. N. A. M. 2018. High Performance Clocks and Gravity Field Determination. Space Sci. Rev., 214(Feb.), 5.

Newton, Isaac. 1687. Philosophiae Naturalis Principia Mathematica. Auctore Js. Newton.

Noether, E. 1918. Invariant Variation Problems. Nachr. D. KÃnig. Gesellsch. D. Wiss. Zu GÃttingen, Math-phys. Klasse 1918: p. 235-237, 235–237.

O'Connell, R. F. 2009. Gravito-magnetism in one-body and two-body systems: Theory and experiments. Page 149 of: Arimondo, E., Ertmer, W., Schleich, W. P., & Rasel, E. M. (eds), Atom Optics and Space Physics.

Paczyński, B., & Wiita, P. J. 1980. Thick accretion disks and supercritical luminosities. A&A, 88(Aug.), 23–31.

Pound, R. V., & Rebka, G. A. 1960. Apparent Weight of Photons. Physical Review Letters, 4(Apr.), 337–341.

Psaltis, D. 2008. Probes and Tests of Strong-Field Gravity with Observations in the Electromagnetic Spectrum. Living Reviews in Relativity, 11(Nov.), 9.

Reynaud, S., Salomon, C., & Wolf, P. 2009. Testing General Relativity with Atomic Clocks. Space Sci. Rev., 148(Dec.), 233–247.

Sachs, R. K., & Wu, H.-H. 1977. General Relativity for Mathematicians.

Schäfer, G. 2009. Gravitomagnetism in Physics and Astrophysics. Space Sci. Rev., 148(Dec.), 37–52.

Shannon, R. M., Johnston, S., & Manchester, R. N. 2014. The kinematics and orbital dynamics of the PSR B1259-63/LS 2883 system from 23 yr of pulsar timing. MNRAS, 437(Feb.), 3255–3264.

Steadman, B. R. 1999. Null geodesics in a rotating dust cloud. Classical and Quantum Gravity, 16(Nov.), 3685–3691.

Stella, L., & Possenti, A. 2009. Lense-Thirring Precession in the Astrophysical Context. Space Sci. Rev., 148(Dec.), 105–121.

Yang, C. N., & Mills, R. L. 1954. Conservation of Isotopic Spin and Isotopic Gauge Invariance. Physical Review, 96(Oct.), 191–195.

Yuan-Hong, L. I., & Jun-Li, L. U. 2011. The Doppler Effect in Curved Space-Time. Journal of Natural Science of Hunan Normal University.