Clock-Comparison Tests of Lorentz and *CPT* Symmetry in Space

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Clock-comparison experiments conducted in space can provide access to many unmeasured coefficients for Lorentz and *CPT* violation. The orbital configuration of a satellite platform and the relatively large velocities attainable in a deep-space mission would permit a broad range of tests with Planck-scale sensitivity.

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A major open challenge in science is understanding physics at the Planck scale, $m_P \simeq 10^{19}$ GeV. Direct experimental access to this scale is impractical, but suppressed effects from it might be observable in tests of exceptional sensitivity. One promising candidate signal is Lorentz violation [1], which might arise in string theory with or without *CPT* violation [2] and is a feature of noncommutative field theories [3]. Observable effects are described by a general standard-model extension allowing for Lorentz and *CPT* violation [4].

Among the sharpest tests of Lorentz symmetry in matter are clock-comparison experiments [5–8]. These search for spatial anisotropies by studying the frequency variation of a Zeeman hyperfine transition as the quantization axis changes orientation. Traditionally, the frequencies of two different colocated clocks are compared as the laboratory rotates with the Earth. Experiments of this type are sensitive to suppressed effects from the Planck scale [9]. Other tests also constrain various sectors of the standard-model extension, involving hadrons [10–14], photons [4,15], muons [16], and electrons [17,18].

In this work, we show that clock-comparison experiments on satellites and other spacecraft can provide wide-ranging tests of Lorentz and *CPT* symmetry with Planck-scale sensitivity. We consider space experiments in a general theoretical context and discuss tests for some specific orbital and deep-space missions, including several approved for the International Space Station (ISS).

The presence of Lorentz and *CPT* violation causes frequency shifts in certain Zeeman hyperfine transitions [9]. In the clock frame, the relevant contributions to these shifts are controlled to leading order by a few parameters conventionally denoted as $\tilde{b}_3^w$, $\tilde{c}_q^w$, $\tilde{d}_3^w$, $\tilde{g}_d^w$, $\tilde{g}_q^w$, where the superscript w is p for the proton, n for the neutron, and e for the electron. These parameters are special combinations of the basic coefficients a_μ^w, b_μ^w, $c_{\mu\nu}^w$, $d_{\mu\nu}^w$, e_μ^w, f_μ^w, $g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$ appearing in the standard-model extension and related to expectation values in the fundamental theory. For example, $\tilde{b}_3^w = b_3^w - m_w d_{30}^w + m_w g_{120}^w - H_{12}^w$, where m_w is the mass of the particle of type w and the subscripts are indices defined in a coordinate system with the 3 direction along the clock quantization axis.

Consider first a clock fixed in a ground-based laboratory. Then, the parameters $\tilde{b}_3^w$, $\tilde{c}_q^w$, $\tilde{d}_3^w$, $\tilde{g}_d^w$, $\tilde{g}_q^w$ vary in time with periodicities determined by the Earth's sidereal angular frequency $\Omega \simeq 2\pi/(23\ \text{h}\ 56\ \text{min})$. To display this time dependence, it is useful to convert these parameters from the clock frame with coordinates $(0, 1, 2, 3)$ to a nonrotating frame with coordinates (T, X, Y, Z). The nonrotating frame should for practical purposes be an inertial reference frame, or at least a frame that is inertial to a degree appropriate to the experimental sensitivity. Possible choices of frame might include, for example, ones associated with the Earth, the Sun, the Milky Way galaxy, or the cosmic microwave background radiation. Previous literature has restricted attention to a nonrelativistic conversion from the clock frame to the nonrotating frame. Under these circumstances, all the above frames are acceptable and existing experimental bounds are unaffected by the choice among them. However, in the context of space-based experiments, the high velocities attainable make it of interest to consider also leading-order relativistic effects due to clock boosts. An Earth-centered choice is then no longer appropriate because it yields distinguishable inertial frames at different times of year. In contrast, frames centered on the Sun, the galaxy, and the microwave background each remain unchanged approximate inertial frames over thousands of years. Any one of these can be used, but the choice must be specified when reporting bounds.

In the experimental context a Sun-based frame is natural, and we adopt it here. For convenience, we fix the spatial origin at the Sun's center with the unit vector $\hat{Z}$ along the Earth's rotation axis, $\hat{X}$, $\hat{Y}$ in the equatorial plane, and $\hat{X}$ pointing towards the vernal equinox on the celestial sphere. The time T is measured by a clock at rest at the origin, with $T = 0$ taken as the vernal equinox in the year 2000. In this frame, the Earth's orbital plane lies at an angle $\eta \simeq 23°$ with respect to the XY plane.

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For the analysis of space-based experiments, it suffices to approximate the Earth's orbit as circular with mean angular frequency $\Omega_\oplus$ and mean speed $\beta_\oplus$. Similarly, a satellite orbit about the Earth can be approximated as circular with mean angular frequency ω_s and mean speed β_s. We denote by ζ the angle between $\hat{Z}$ and the axis of the satellite orbit and by α the azimuthal angle at which the orbital plane intersects the Earth's equatorial plane. Various perturbations cause α to precess.

In the Sun-based frame, the instantaneous clock boost is $\vec{V}(T) = d\vec{X}/dT$, where the instantaneous spatial location $\vec{X}(T)$ of the clock depends on the spacecraft and Earth trajectories. Infinitesimal time intervals in the clock frame are dilated relative to ones in the Sun-based frame by an amount controlled by $\vec{V}(T)$. An accurate conversion between the two times must allow for effects such as small perturbations in $\vec{V}(T)$ and the gravitational potential. However, these complications are irrelevant when two clocks at a given location are compared: conventional relativity predicts an identical rate of advance. In contrast, in the presence of Lorentz and CPT violation two colocated clocks involving different atomic species typically behave differently, producing a signal that cannot be mimicked in conventional relativity.

The orientation of the clock quantization axis may change as a satellite orbits, depending on the flight mode. For brevity in specific examples below, we assume a flight mode and clock configuration such that the clock quantization axis is instantaneously tangential to the satellite's circular trajectory about the Earth. The clock frame can then be chosen to have 3 axis parallel to the satellite motion about the Earth, 1 axis pointing towards the center of the Earth, and 2 axis perpendicular to the satellite orbital plane. This configuration is, for example, currently planned for some clock experiments aboard the ISS. However, our general methodology and results hold for arbitrary orientations of the clock quantization axis [19] and for various spacecraft flight modes.

The conversion of a signal in the clock frame to the Sun-based frame involves combining the boost $\vec{V}(T)$ with the rotation of the clock as it orbits the Earth. According to the above discussion, components of the coefficients for Lorentz violation in the clock frame are to be expressed in terms of components in the Sun-based frame. For example, the component b_3^w becomes

$$\begin{aligned} b_3^w = b_T^w\{\beta_s - \beta_\oplus[&\sin\Omega_\oplus T(\cos\alpha \sin\omega_s\Delta T + \cos\zeta \sin\alpha \cos\omega_s\Delta T) \\ &- \cos\eta \cos\Omega_\oplus T(\sin\alpha \sin\omega_s\Delta T - \cos\zeta \cos\alpha \cos\omega_s\Delta T) + \sin\eta \cos\Omega_\oplus T \sin\zeta \cos\omega_s\Delta T]\} \\ &- b_X^w(\cos\alpha \sin\omega_s\Delta T + \cos\zeta \sin\alpha \cos\omega_s\Delta T) - b_Y^w(\sin\alpha \sin\omega_s\Delta T - \cos\zeta \cos\alpha \cos\omega_s\Delta T) \\ &+ b_Z^w \sin\zeta \cos\omega_s\Delta T\,, \end{aligned} \tag{1}$$

where $\Delta T = T - T_0$ is the time measured from a reference time T_0. This equation holds to leading order in linear velocities and so neglects effects such as the Thomas precession. The result (1) for the component b_3^w must be combined with results for other coefficients to yield the Sun-frame expression for the observable parameter $\tilde{b}_3^w$. A similar procedure yields the other observables $\tilde{c}_q^w$, $\tilde{d}_3^w$, $\tilde{g}_d^w$, $\tilde{g}_q^w$. The full expressions are lengthy and depend on various combinations of basic coefficients for Lorentz and CPT violation, on trigonometric functions of various angles and frequency-time products, and on $\beta_\oplus$ and β_s.

An immediate advantage of space-based experiments is the direct accessibility of all spatial components of the basic coefficients for Lorentz and CPT violation. Existing ground-based clock-comparison experiments seek frequency variations as the Earth rotates, and the fixed rotational axis implies that the signal is independent of certain spatial components. For example, in these experiments the parameter $\tilde{b}_3^w$ provides sensitivity only to the nonrotating-frame components $\tilde{b}_X^w$, $\tilde{b}_Y^w$, which in turn involve a restricted subset of components of b_μ^w, $d_{\mu\nu}^w$, $g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$. In contrast, an orbiting satellite can access all spatial components. Typically, the satellite orbital plane differs from the equatorial plane, thus offering different sensitivity from traditional Earth-based experiments. In addition, the precession of the satellite orbital plane makes it feasible to sample all spatial directions.

In space, the relatively short orbital periods ($\omega_s \gg \Omega$) imply that the time required for collecting an adequate data set can be much reduced. For example, the ISS period is about 92 min, so an experiment on the ISS could be completed about 16 times faster than a traditional Earth-based one, better matching clock stabilities and reducing the needed time from months to days. This makes practical an analysis of the leading relativistic effects due to the instantaneous speed $\beta_\oplus \simeq 1 \times 10^{-4}$ of the Earth in the Sun-based frame, which in turn provides sensitivity to many more types of Lorentz and CPT violation. Existing ground-based experiments typically take data over months, during which the Earth's velocity vector changes significantly. In space, the shorter time scale for data set collection means that this vector is approximately constant. An experiment could therefore be viewed as involving a single inertial frame, which would allow direct extraction of leading relativistic effects.

For space-based experiments, the above effects combine to yield an overall sensitivity to many types of Lorentz and CPT violation that remain unconstrained to date. Consider, for example, a clock-comparison experiment sensitive to $\tilde{b}_3^w$ for some w. In the Sun-based frame and for each w, $\tilde{b}_3^w$ is a combination of the basic coefficients b_μ^w, $d_{\mu\nu}^w$, $g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$ for Lorentz violation, which include 35 independent observable components if allowance is made for the effect of field redefinitions. A traditional ground-based experiment is sensitive to 8 of these [20]. We find the same type of experiment mounted on a space platform would acquire sensitivity to all 35.

For some components, the Lorentz and *CPT* reach is suppressed by a factor of $\beta_\oplus$. This is the dominant linear boost factor in the relativistic corrections. However, space-based clock-comparison experiments would also be sensitive to first-order relativistic effects proportional to β_s. The corresponding effects in traditional Earth-based experiments are harder to study and in any case are further suppressed by a factor of Ω/ω_s, which is, for example, about 6×10^{-2} for the ISS.

Among the order-β_s effects is a seemingly counterintuitive one: in space-based experiments a dipole shift can generate a detectable signal at frequency $2\omega_s$. This contrasts with the usual analysis of ground-based experiments, where signals with frequency 2Ω arise only from quadrupole shifts. Consider, for example, the parameter $\tilde{b}_3^w$. Nonrelativistically, this parameter is the third component of a vector and so leads only to a signal at frequency ω_s. However, $\tilde{b}_3^w$ contains d_{03}, which behaves like a two-tensor in a relativistic treatment incorporating first-order effects from β_s and so can generate a signal at frequency $2\omega_s$. For example, when the Earth is near the northern-summer solstice, the coefficient C_2 of $\beta_s \cos 2\omega_s \Delta T$ in the expression for $\tilde{b}_3^w$ in the Sun-based frame includes a dependence on purely spatial components of $d_{\mu\nu}^w$:

$$C_2 \supset \frac{m}{8}\{\cos 2\alpha(3 + \cos 2\zeta)(d_{XX}^w - d_{YY}^w) + (1 - \cos 2\zeta)(d_{XX}^w + d_{YY}^w - 2d_{ZZ}^w) - 2\sin 2\zeta[\cos\alpha(d_{YZ}^w + d_{ZY}^w) - \sin\alpha(d_{ZX}^w + d_{XZ}^w)] + (3 + \cos 2\zeta)\sin 2\alpha(d_{XY}^w + d_{YX}^w)\}. \quad (2)$$

Monitoring of the frequency $2\omega_s$ therefore offers sensitivity to all observable spatial components of $d_{\mu\nu}^w$.

We focus next on the special case where the orbiting platform is the ISS, for which $\beta_s \simeq 3 \times 10^{-5}$ and $\zeta \simeq 52°$. Among the instruments planned for flight on the ISS are H masers, laser-cooled Cs and Rb clocks, and superconducting microwave cavity oscillators [21–24]. We provide here a simplified theoretical analysis, applicable to possible Lorentz tests with all except the oscillators, which are discussed elsewhere [25]. Note that the practical implementation of these experiments requires careful consideration of various technical issues, including the limitations imposed by the ambient magnetic fields on the ISS. For simplicity, we assume the signal clock is referenced to a colocated clock that is insensitive to leading-order Lorentz and *CPT* violation, such as an H maser operating on its clock transition $|1,0\rangle \rightarrow |0,0\rangle$ [26].

An H maser could also be used as the signal clock. An experiment could be envisaged analogous to a recent Earth-based Lorentz and *CPT* test, which measured the maser transition $|1,\pm1\rangle \rightarrow |1,0\rangle$ using a double-resonance technique [8]. This offers sensitivity to the parameters $\tilde{b}_3^p$ and $\tilde{b}_3^e$ in the clock frame without the interpretational issues associated with experiments using atoms with more complex nuclei. The relatively short ISS orbital period implies only about a day of continuous operation could suffice to obtain a data set roughly comparable to that obtained over the course of four months in a traditional Earth-based experiment. The orbital inclination ($\zeta \neq 0$) and the possibility of repeating the experiment for a different value of α means that for $w = e, p$ all spatial components of b_μ^w, $m_w d_{\mu\nu}^w$, $m_w g_{\lambda\mu\nu}^w$, $H_{\mu\nu}^w$ could be sampled. Assuming that the previous sensitivity of about 500 μHz can also be achieved in space, several components presently unbounded would be tested at the level of about 10^{-27} GeV, while others would be tested at about 10^{-23} GeV. Searching also for a signal at frequency $2\omega_s$ would permit cleaner bounds on some spatial components of $m_w d_{\mu\nu}^w$, $m_w g_{\lambda\mu\nu}^w$ of order 10^{-23} GeV. We find about 50 components of coefficients for Lorentz violation that are currently unconstrained could be measured with Planck-scale sensitivities.

In a laser-cooled ^{133}Cs clock, the standard clock transition $|4,0\rangle \rightarrow |3,0\rangle$ is insensitive to Lorentz violation and could therefore be used as a reference. For the signal, a Zeeman hyperfine transition such as $|4,4\rangle \rightarrow |4,3\rangle$ must be measured. The electronic configuration of ^{133}Cs involves an unpaired electron, so the sensitivity to electron parameters is similar to that of the H maser. The Schmidt nucleon for ^{133}Cs is a proton with angular momentum 7/2, which offers sensitivity to all clock-frame parameters $\tilde{b}_3^p$, $\tilde{c}_q^p$, $\tilde{d}_3^p$, $\tilde{g}_d^p$, $\tilde{g}_q^p$ and thus yields both dipole and quadrupole shifts. In particular, components of $c_{\mu\nu}^p$ could be tested. A traditional ground-based experiment using the $|4,4\rangle \rightarrow |4,3\rangle$ transition has reached the level of about 50 μHz [6]. The duration of an analogous experiment on the ISS would be reduced 16-fold. In addition, studies of the signal at frequency $2\omega_s$ would allow a measurement of the spatial components of $c_{\mu\nu}^p$ at the level of 10^{-25} and other components at about 10^{-21}. First measurements with Planck-scale sensitivity of about 60 components of coefficients for Lorentz and *CPT* violation would be possible.

The features of an experiment using ^{87}Rb are similar in many respects. The standard $|2,0\rangle \rightarrow |1,0\rangle$ clock transition is insensitive to Lorentz and *CPT* violation. However, a Zeeman hyperfine transition such as $|2,1\rangle \rightarrow |2,0\rangle$ could be adopted as a signal clock. Since ^{87}Rb has an unpaired electron, its sensitivity to electron parameters is similar to that of an H maser or a Zeeman hyperfine transition in ^{133}Cs. The Schmidt nucleon for ^{87}Rb is a proton with angular momentum 3/2, so the sensitivity to proton parameters is also analogous to that of the ^{133}Cs case up to factors of order unity. One potential advantage is that the nuclear configuration has magic neutron number, so theoretical calculations are likely to be more reliable and experimental results cleaner [9]. Like the ^{133}Cs case, numerous Lorentz and *CPT* tests could be performed.

Other types of spacecraft could also provide valuable Lorentz and *CPT* tests. Speeds an order of magnitude greater than $\beta_\oplus$ could be accessible in certain missions. For example, the proposed SpaceTime experiment [27] would fly colocated $^{111}Cd^+$, $^{199}Hg^+$, and $^{171}Yb^+$ ion clocks on a solar-infall trajectory from Jupiter, attaining $\beta \simeq 10^{-3}$. The craft would rotate several times per minute, so even 15 min might suffice to acquire a complete data set for Lorentz and *CPT* tests. For all three clocks, the standard clock transitions $|1,0\rangle \rightarrow |0,0\rangle$ are insensitive to Lorentz and *CPT* violation and so can be used as references. A Zeeman hyperfine transition such as $|1,1\rangle \rightarrow |1,0\rangle$ is a possible signal clock. The electronic configuration then permits sensitivity to electron parameters. Also, the Schmidt nucleon for all three isotopes is a neutron with angular momentum $1/2$, so all three clocks are sensitive to the neutron parameters $\tilde{b}_3^n$, $\tilde{d}_3^n$, $\tilde{g}_d^n$ in the clock frame. These parameters cannot be directly measured in the ISS experiments discussed above. Monitoring the signal at the spacecraft rotation frequency ω_{ST} and also at $2\omega_{ST}$ would again permit numerous measurements of unconstrained coefficients for Lorentz and *CPT* violation. The large boost provides experiments of this type an intrinsic order of magnitude greater sensitivity to Lorentz and *CPT* violation than measurements performed either on the Earth or in orbiting satellites.

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[19] Note that achieving optimal sensitivity to certain components can require specific clock orientations.

[20] In principle, an Earth-based experiment placed on a continuously rotating turntable could access many more coefficients, but the practical implementation of this appears challenging. However, a novel type of ground-based experiment is presently under development, in which the orientation of the apparatus could be reversed every few minutes [L. R. Hunter (private communication)]. This ingenious experiment would permit the measurement of many more coefficients than traditional ground-based tests. Note that its sensitivity differs significantly from that of space-based experiments, even if identical signal and reference clocks are used. The two types of experiments should therefore provide valuable complementary measurements.

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