Optical Atomic Clock aboard an Earth-orbiting Space Station (OACESS): Enhancing searches for physics beyond the standard model in space

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Abstract

We present a concept for a high-precision optical atomic clock (OAC) operating on an Earth-orbiting space station. This pathfinder science mission will compare the space-based OAC with one or more ultra-stable terrestrial OACs to search for space-time-dependent signatures of dark scalar fields that manifest as anomalies in the relative frequencies of station-based and ground-based clocks. This opens the possibility of probing models of new physics that are inaccessible to purely ground-based OAC experiments, for example models where a dark scalar field is strongly screened near Earth's surface.

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1 Introduction

Recent advances in optical atomic clocks (OAC) will provide new measurement capabilities with which the Standard Model (SM) and General Relativity (GR) that can be tested to unprecedented precision [1]. These clocks utilize ensembles of laser-cooled atoms as a frequency reference, with technologies similar to those at the heart of the ISS-based Cold Atom Lab (CAL) [2]. The clock signal is derived from an ultra-stable laser which is frequency-locked to an narrow optical transition at 100's of THz. Terrestrial OAC have now achieved stability and accuracy at the 10^{-18} level in fractional frequency units [3–10], orders of magnitude better compared with the record caesium microwave frequency standards [11].

It has recently been realized that space-based clocks should offer a significant advantage over ground-based clocks to test certain models of dark-sector particles, fields, or entities (such as dark matter and dark energy) which are absent in the SM; specifically, for dark scalar fields where the scalar field is strongly screened near Earth's surface [12–14] (see also [15–17] for earlier work on screening in scalar-field models). The OACESS mission concept therefore addresses two priorities for BPS: 1) By establishing high-precision OAC and ground-to-space time transfer technologies in Earth's orbit, it provides capabilities for **science that can be done in space, with anticipated value to humans on Earth**, and 2) The possibility of detecting dark fields which are otherwise screened near Earth's surface offers **science that can be done in space, because the reduced gravity environment enables cleaner analysis of fundamental research questions.**

We propose a Sr optical lattice clock operating aboard an Earth-orbiting space station as a pathfinder science mission to enable unprecedented capabilities in searches for signatures of physics beyond the SM. Comparison of the OACESS clock with terrestrial OAC via optical two-way time-frequency transfer (O-TWTFT) [11, 18] will enable tests of temporal and spatial variations of the fundamental constants of nature that can arise in various dark-sector models, including ultra-low-mass dark matter and dark energy, as well as in quantum gravity. In this way, OACESS will serve as a pathfinder for dedicated missions (e.g., FOCOS [19]) to establish high-precision OAC as space-time references in space.

As a space-station-based multi-user research campaign, we also consider the inclusion of high-precision sensors for complementary searches for dark-matter signatures, including magnetometers, accelerometers, optical cavities and interferometers. Additional sensors or measurement combinations allow for complementary searches for dark-matter signatures. Vapor-cell-based magnetometers are routinely used in real-life applications. Mature laser technology, microfab cells and optical assembly techniques allow for a compact low Size, Weight, and Power (SWaP) piggyback device.

2 Probing the dark sector with space-based clocks

Determining the properties of dark matter and dark energy is one of the grand challenges of our time. Ultra-low-mass (sub-eV mass) bosonic particles are an excellent candidate to explain the dark matter and dark energy, and can also serve as more general dark-sector components that do not necessarily play a significant role in cosmology. Atomic clocks have been proposed as sensitive probes of dark scalar (spin-0) fields that induce temporal or spatial variations of the fundamental constants of nature, including in models of dark matter [20–22, 12], solitons [23, 13], and bursts of relativistic scalar particles [24, 14].

Let us consider the following interaction Lagrangian describing the coupling of a real scalar field ϕ to ordinary matter at low energies (see, e.g., [21, 22]):

$$\mathcal{L}_{\text{int}}^{(n)} = \left(\frac{\phi}{\Lambda_{\gamma,n}}\right)^n \frac{F_{\mu\nu}F^{\mu\nu}}{4} - \left(\frac{\phi}{\Lambda_{e,n}}\right)^n m_e\bar{\psi}_e\psi_e - \left(\frac{\phi}{\Lambda_{N,n}}\right)^n m_N\bar{\psi}_N\psi_N \,, \tag{1}$$

where F is the electromagnetic field tensor, ψ_e denotes the electron field, and ψ_N denote the nucleon fields. The parameters $\Lambda_{i,n}$ denote the effective new-physics energy scales of the underlying model, with n being a positive integer; higher energy scales correspond to more feeble interactions between the scalar field and SM fields. In this section, we employ the natural units $\hbar = c = 1$.

The most commonly considered values of n in Eq. (1) are $n = 1$ (*linear portal*) and $n = 2$ (*quadratic portal*). The quadratic portal is of particular interest to experiments employing at least one atomic clock in space, since the scalar field can be strongly screened near the surface of and inside Earth as well as other large dense bodies [12–17]. When the scalar field is strongly screened inside Earth, the scalar-field amplitude can be suppressed by the factor of $\sim h/R$ near the surface of a spherical dense body, where h is the height above the surface of the body and R is the radius of the body; for a typical height of a ground-based atomic clock of $h \sim 1$ m, we have $h/R_\oplus \sim 10^{-7}$, which means that the utilization of space-based clocks, such as in OACESS, can provide an enormous advantage.

The Lagrangian (1) induces the following changes in the apparent values of the electromagnetic fine-structure constant α and the fermion masses [21, 22]:

$$\frac{\delta\alpha}{\alpha} \approx \left(\frac{\phi}{\Lambda_{\gamma,n}}\right)^n, \quad \frac{\delta m_e}{m_e} = \left(\frac{\phi}{\Lambda_{e,n}}\right)^n, \quad \frac{\delta m_N}{m_N} = \left(\frac{\phi}{\Lambda_{N,n}}\right)^n . \tag{2}$$

The response of a clock transition frequency ν to apparent variations of one or more of the fundamental constants $X = \alpha, m_e, m_N$ can be parameterized in terms of the *relative sensitivity coefficients* K_X, according to:

$$\delta\nu/\nu = \sum_X K_X \, \delta X/X \,. \tag{3}$$

In the non-relativistic limit, an archetypal optical atomic transition frequency scales proportionally to the Rydberg constant, $\nu \propto m_e\alpha^2$, and so $K_\alpha = +2$, $K_{m_e} = +1$ and $K_{m_N} = 0$. In ground-to-space comparisons of a *single* optical clock transition, which involve an independent determination of the clock height difference e.g. via a combination of laser ranging and either orbital position or gravimeter data, the effective sensitivity coefficients are $K_\alpha^{\text{eff}} \approx +2$, $K_{m_e}^{\text{eff}} \approx +1$, $K_{m_N}^{\text{eff}} \approx -1$ in the non-relativistic limit [13].

In Figs. 1(a) and 1(b), we present the projected sensitivity of a clock operating in low Earth orbit (e.g., ISS), assuming an absolute fractional clock accuracy of $2\times10^{-16}/\sqrt{\tau/\text{s}}$ with a peak accuracy of 10^{-18}, in the context of two different scalar-field models:

- In Fig. 1(a), static or quasi-static apparent variations of m_e with changing height above Earth's surface, arising in a scalar-field model that permits the production of cosmological domain walls [13]. Here we have chosen model parameters such that a single cosmological domain wall would contribute to the present-day mass-energy fraction of the Universe at the level of one part in 10^{20}; however, our sensitivity estimate also equally applies if there are no

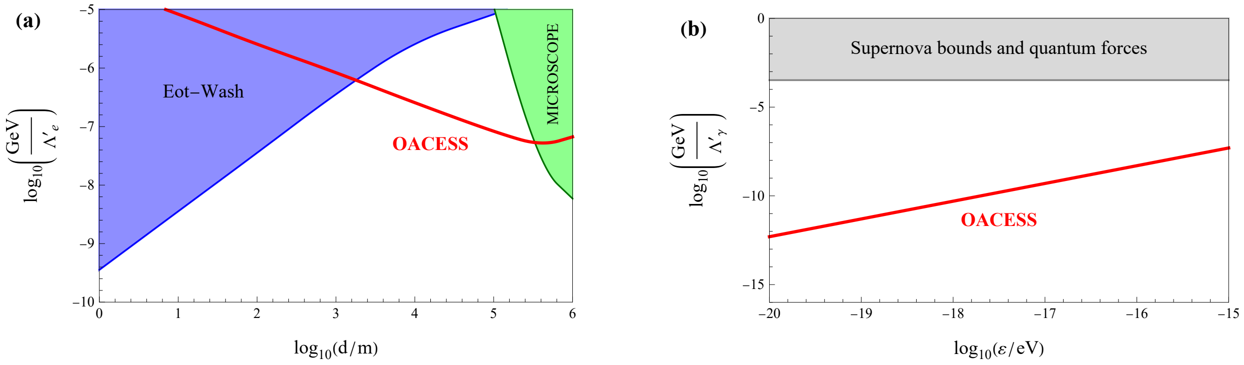

Figure 1: Projected sensitivity of a Sr OACESS clock on board the ISS (red curve) to **(a)** static or quasi-static apparent variations of m_e with changing height above Earth's surface, arising in a scalar-field model that permits the production of cosmological domain walls, and **(b)** transient changes in the apparent value of α due to the passage of a relativistic scalar wave from an intense burst of extraterrestrial origin. The figures are for the quadratic ($n = 2$) interactions of the scalar field with **(a)** the electron and **(b)** the electromagnetic field. In subfigure **(a)**, the blue and green regions correspond to torsion-pendulum-type constraints from the ground-based Eöt-Wash experiment and the space-based MICROSCOPE mission, respectively, obtained by rescaling the limits in Ref. [13] for the model parameters described in the main text of our present paper. In subfigure **(b)**, the grey region corresponds to existing constraints from supernova energy-loss bounds and short-range tests of gravity searching for quantum forces [16].

domain walls of cosmological origin. The apparent value of m_e changes over a characteristic height of $\sim \min(d, R_\oplus)$ away from Earth's surface, where d is the thickness of a (possible) domain wall of cosmological origin, and so the comparison of the space-based OACESS clock with an analogous ground-based clock can offer an enormous advantage over purely ground-based clock comparisons such as in Ref. [25] for $d \gtrsim 1$ km.

- In Fig. 1(b), transient changes in the apparent value of α due to the passage of a relativistic scalar wave from an intense burst of extraterrestrial origin [14, 24]. Here we have chosen burst parameters that yield a coherent burst over the entire relevant range of scalar particle energies ε and have assumed that the same type of scalar particle makes no contribution towards the matter-energy content of the Universe (beyond the negligible fraction due to the bursts themselves). The use of a space-based clock network with multiple nodes would allow for the determination of the direction to the burst source.

In both cases, analogous ground-based clock experiments have insufficient sensitivity to probe the relevant parameter space in these models due to strong screening of the scalar field by Earth's atmosphere (see Refs. [13] and [14] for details). Experiments utilizing space-based optical clocks therefore open up possibilities that are currently inaccessible to purely ground-based experiments.

3 Space Station Enabled Optical Clock Hardware

Key components for a space-based optical atomic clock payload include the Science Module (in which the atoms are produced, cooled, and interrogated), the laser and optical system (including the ultra-high stability clock laser), and the clock signal distribution system (including the optical frequency comb (OFC) for down-converting high-precision clock signals from the optical domain and space-to-ground comparison via O-TWTFT). The payload is illustrated in Figure 2. In the following, we briefly discuss the primary components for OACESS and the ongoing efforts from various institutions worldwide towards supporting a near-term Earth-orbiting optical clock mission.

Science Module

OACESS will require a rugged Science Module that incorporates the physics package (vacuum chamber), magnetic coils, optomechanics, magnetic shields, and thermal control systems in a low-SWaP design. The physics package will consist of a low-power, high-flux atom source and an ultra-high-vacuum (better than 10^{-10} torr) "Science Cell" with exceptional optical access to accommodate three retro-reflected pairs of laser beams for the Magneto-Optical Trap (MOT), an 813 nm lattice laser, a clock laser, optical pumping beams, and an independent imaging path. Mature solutions currently exist for the miniaturized Sr source [26, 27]. We envision that the science cell, vacuum pumps, magnetic coils, optomechanics, magnetic shields, cooling, electronics, and control/imaging systems can be based on CAL heritage [2] as well as ongoing DLR activities (SOLIS-1G).

However, because some types of OACESS dark-sector searches rely on time-dependent comparisons of ultra-high-precision clocks, it will assuredly require greater environmental control with respect to CAL. ***Influences and mitigation plans for the leading clock systematic errors will therefore be an integral part of this study. The development and use of ground testbeds for analyzing/testing OACESS designs for functionality and unanticipated systematic shifts will be critical.***

Laser and Optical System

The operation of OACESS requires a laser system capable of two-color laser cooling, state preparation, coherent transfer and trapping in an optical lattice at the magic wavelength and ultra-stable interrogation of the clock transition [3]. The required wavelengths are shown in Figure 2. Here, the ultra-stable clock laser system will combine mature cavity-stabilized laser designs from terrestrial labs [3–10] with flight qualified laser system designs (e.g., for the GRACE-FO mission [28]).

Strontium optical clock technologies have matured to the point where all needed lasers can be provided by diode lasers. Diode-laser-based systems already operate in experiments at the Bremen drop tower, on sounding rockets, and in CAL to study ultra-cold rubidium and potassium atoms [29, 30, 40, 2]. Laser payloads and optical frequency references have been developed for operation on sounding rockets and reached TRL 9 on such sub-orbital vehicles through flight mission operation [31–34]. These payloads feature diode laser systems which are based on a micro-integrated laser technology platform, providing compact, robust and

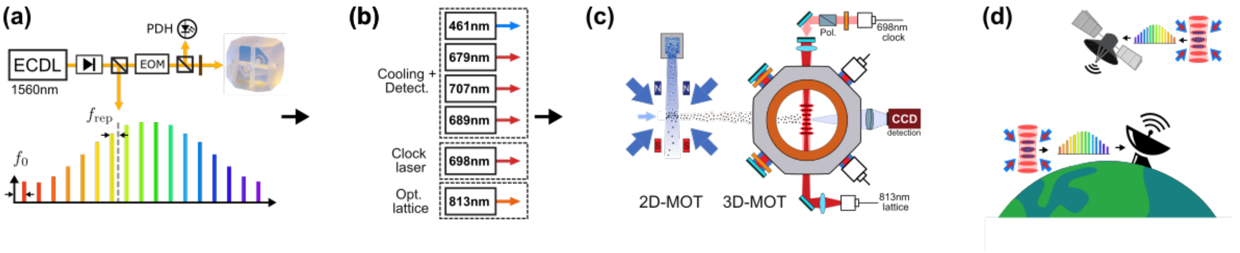

Figure 2: Schematic representation of the payload. **(a)** Compact and high stability clock laser will be stabilized via a high-finesse optical cavity and locked to a stable optical frequency comb reference for short- and long-term stability. **(b)** The diode laser system in OACESS will be based on technologies operated in sounding rocket missions which are currently developed further for space applications. **(c)** The science module is matured from CAL and JPL heritage to provide high atom flux of ultracold strontium gases with low SWaP. **(d)** O-TWTFT will allow precise space-to-ground comparisons of high-precision optical clocks worldwide.

energy-efficient semiconductor laser modules. Moreover, a system for laser cooling and atom interferometry with ^{87}Rb atoms was launched in 2017 (MAIUS) [35] and a high-performance optical frequency reference based on molecular iodine (JOKARUS mission) has also been launched [42, 36].Currently, laser systems with even lower SWaP are developed for future operation on cubesats [41]. ***Development of a robust, low SWaP clock laser system will benefit from early development of ground testbeds to validate the design and performance of the clock***.

Frequency comparison

We consider frequency-comb-based O-TWTFT as a promising method for achieving space-to-ground clock comparisons below the 10^{-18} level. Here, laser light stabilized by the optical clocks would be transmitted to optical frequency combs. OFC pulses from Earth clocks and from the space clock would then be simultaneously exchanged via a free-space optical link, thereby sampling common air paths in each direction and mitigating the atmospheric degradation of the signals. Recent demonstrations achieve similar performance over a 1.5 km free-space link between optical clocks at JILA and NIST, Boulder [11, 18] and, by synchronizing OC off of a flying quadcopter at closing velocities of up to 20 m/s [37].

Frequency combs have already been operated on suborbital vehicles and successfully demonstrated optical frequency measurements on two sounding rocket flights [33] and are currently developed for operation on the ISS (COMPASSO). Using fiber amplifiers and second harmonic generation, the spectrum from 400 nm - 2000 nm can be covered. In this way, all lasers required for clock operation could be referenced directly to the comb, allowing for additional stabilized laser sources for high-performance space-based optical to ground links. ***For this mission, mature designs for a robust, low SWaP frequency comb will need to be space qualified. In addition, the promising O-TWTFT transfer scheme needs to be validated for orders of magnitude longer length scales and Doppler shifts for the ground-to-space OC comparisons***.

4 Summary

OACESS aims to serve as a pathfinder science mission to search for space-time-dependent signatures of dark scalar fields while establishing the technologies for high-precision optical atomic clocks in space. This mission will directly leverage the developments and lessons learned from the recent and ongoing campaigns of NASA's Cold Atom Lab (CAL), several DLR sounding rocket missions, that demostrated laser systems, BEC based interferometery, optical atomic and molecular frequency references, as well as future missions under development like the NASA/DLR BECCAL. As summarized in the BPS Topical White paper "Space-Time Referencing: atomic clocks, laser links and applications", space-based clocks and Earth-space timing links, building off of the technologies matured by OACESS, can provide enabling capabilities for geodesy, Earth sciences, navigation, world-wide time transfer, and fundamental physics including testing the foundations of General Relativity and searching for physics beyond the Standard Model.

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