# SpaceTime Mission: Clock Test of Relativity at Four Solar Radii

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**Abstract.** SpaceTime is a mission concept developed to test the Equivalence Principle. The mission is based on a clock experiment that will search for a violation of the Equivalence Principle through the observation of a variation of the fine structure constant, $\alpha$. A spatio–temporal variation of $\alpha$ is expected in some string theories aimed at unifying gravity with other forces in nature. SpaceTime uses a special tri–clock instrument on a spacecraft which approaches the sun to within four solar radii. The instrument consists of three trapped ion clocks based on mercury, cadmium, and ytterbium ions, in the same environment. This configuration allows for a differential measurement of the frequency of the clocks and the cancellation of perturbations common to the three. The observation of any frequency drift between each of the clocks, as the tri–clock instrument approaches the sun, signals the existence of a scalar partner to the tensor gravity. Some relevant details of the mission design are discussed in the paper.

## 1 Introduction

The unification of gravity with other forces of nature is arguably the most urgent problem in theoretical physics. Yet the unification program, initiated by Albert Einstein shortly after his introduction of general relativity, has proved to be a difficult challenge and remains an open problem today. The lack of a clear path to unification is even more frustrating since the two underlying theories, the quantum field theory and general relativity, have been separately immensely successful. Quantum field theory is widely regarded as the most successful theory in physics, capable of reproducing details of interaction for all matter. The predictions of this theory have been upheld by the experimental scrutiny in numerous tests. General relativity, on the other hand, has widened our picture of reality, and helped us consider the birth of the Universe, the cosmological evolution, and exotic objects such as the black hole. In the past eighty years since its introduction, this theory has also withstood the most exacting scrutiny that experimental physics has been able to devise [1]. Experimental tests and observations performed in vastly different conditions, ranging from the weak gravity of solar system, to the strong fields of binary pulsars, have all failed to reveal any violation of general relativity. In fact the failure of these very elaborate experiments with their impressive sensitivity in finding any violation has branded them with the label “Null Experiments”, prompting the cynics to declare these tests as measuring zero with ever higher accuracy!

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Yet the impetus behind devising other, more sensitive, tests of general relativity is the unification, itself. Amongst promising candidates for the unification program, string theories stand out since they evidently have the ingredients necessary to accomplish the task. All viable string theories, nevertheless, require a massless scalar field partner to the tensor gravity, in contradiction to Einstein's Equivalence Principle (EEP), the pillar on which general relativity and other metric theories of gravity stand. This reality has led to a widespread belief among theorists that EEP must be violated, and experiments with requisite sensitivity can detect such violation. Thus the experimental tests of EEP now hold the promise of uncovering the range of validity of general relativity. And since some string theories make specific predictions regarding the nature and strength of the EEP violating scalar fields [2], sensitive tests of the EEP also stand to identify viable string theories.

That a violation of EEP will signal evidence for new physics extends beyond the promise of the unified fields; it directly confronts some of the most pressing questions in cosmology. There have been a number of recent suggestions that the so called "cosmological constant problem" may be linked to the presence of a scalar (quintessence) field which could be manifested by a violation of the Equivalence Principle [3].

Among various approaches to test general relativity, atomic clock tests are particularly significant since they represent a direct test of the coupling of gravity to the electromagnetic field. In a recent paper [4] we have extended the ability of atomic clocks in testing general relativity to a local test of the variation of the fine structure constant, $\alpha$. A variation of the fine structure constant will signal a violation of the EEP [1]. On the other hand, a spatiotemporal variation of $\alpha$, the coupling constant of the electromagnetic field, on the Hubble time scale is also implied by the dilaton and other scalar fields (moduli), which are the necessary partners of the tensor gravity field in string theories [5]. So a clock comparison test can fulfill the promise of aiding the unification program by pointing to the viability, or not, of string theories predicting a variation of fundamental coupling constants.

A clock test near the sun is particularly suitable to test the variation of $\alpha$, since it can do so with a sensitivity far beyond that achievable on or near Earth. Finally, clock tests are also useful as a needed complement to "free fall" tests of general relativity. In the latter type of tests, the specifics of the coupling of gravity to any, or various, matter fields must be inferred from apportioning any observed difference in free fall of two, or more, test masses to various types of (mass) energy. Since the coupling of the dilaton field to the Coulomb energy dominates, when combined with clock tests (which are strictly based on atomic transitions driven only by the electromagnetic field) free fall tests will offer a vastly clearer picture of the details of the coupling of gravity to matter fields.

In the following section we will motivate a mission concept to fly a special tri–clock to within four solar radii of the sun in search for the observation of a varying $\alpha$. This mission is referred to as SpaceTime. We will describe the tri–