Precision Clocks in Space and α-Variations

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Abstract:
Important developments both in theoretical and observational cosmology have fueled considerable interest in searches for variations of the fine structure constant. Experimentally, Webb et al have found evidence for a cosmological variation of the fine structure constant through an analysis of the absorption lines in galactic halos from quasar-emitted light. Recently developed small ion atomic clocks enable Solar System tests for equivalence principle (EP) violating α-variations by way of rate-comparisons of three ultra-stable atomic clocks near-to and far-from the sun where gravitational red-shift changes are more than 10^4 larger than in low Earth orbit. No space tests of the EP have been made in nearly 30 years, since the GP-A hydrogen maser reached a 10,000 km apogee confirming EP red-shift predictions to ~1 part in 10^4. Today's small ion clocks, nearly 100x more stable and 100x smaller than the GP-A H-maser, could probe for EP violating scalar fields near the sun for mission costs comparable to low Earth orbiters and improve the GP-A sensitivity by 5 to 6 orders of magnitude.

Introduction:

A large number of recent theoretical papers have developed scenarios for spatial and temporal variations of the fine structure constant, α. Many of these papers have been stimulated by the measurements of Webb et al [2001, 2003] showing a possible cosmological variation of the fine structure constant. Theoretical cosmologists [Damour, 2003] predict possible α-variations from string model efforts to achieve Grand Unification via an Equivalence Principle (EP) violating scalar field, ϕ, associated with the gravitational field. The accelerated expansion of the universe, driven by dark energy, also suggests a nearly massless scalar field that violates EP [Parkinson et al, 2003] and would lead to α-variations. The theoretical nature of such scalar fields has even evolved to accommodate the tight experimental limits set by Earth-based searches for EP violations. Indeed, in the 'chameleon' scenario [Khoury et al, 2003], the mass and range of this scalar field depends upon the local matter density, so that the EP violating 5^{th}-force mediated by ϕ may be as small as 1mm on the surface of Earth and yet be several AU or more in the interplanetary regions of the solar system, far from planetary masses. In fact, EP violations are much larger in deep space, according to chameleon cosmology. In this paper we describe a solar system experiment with three small high-precision atomic clocks to test for a spatial variation of α (as predicted in all above mentioned references) in the strong gravitational field near the Sun and in regions a few AU from planetary masses.

For many years, flight engineers at JPL have studied close solar flyby missions and have designed space-craft that can survive to within 4 solar radii while (room temperature) flight payload instruments carry out sensitive measurements. Variations of this scalar field ϕ along the spacecraft trajectory will lead to a change in the relative frequency of three atomic clocks, and will be used to probe for the variations of α to the 10^{-16} level. Since the response of each clock to a change in α has a specific signature, this measurement can provide unambiguous results, readily distinguishable from magnetic field induced clock shifts that may be encountered near the sun. This deep space test of the Equivalence Principle will be the first ever made spanning over AU distances, sampling the low and high-density regions of the solar system to a level far exceeding present day Earth-based experiments. This approach to EP tests is based on small ultra stable ion clocks now under development at JPL for deep space operation. Since each of these ultra-stable ion clocks are quite small (2-3 kg) and developed for deep space operation, no other EP measurement technology is able to execute so sensitive an EP test in deep space, far from Earth.

History:

Atomic clocks have traditionally been used to test the prediction of general relativity. The first such space test was performed in 1976 by NASA's Gravity Probe A, where the rate of a hydrogen maser clock during a (two-hour) sub-orbital trajectory was compared to that of a similar clock on the Earth's surface [Vessot et al., 1980]. This measurement verified the predictions of the EP clock shift to a part in 10^4, a precision that still stands unchallenged today. More recently, we showed that variations of α would force a corresponding change in the relative frequency of two hyperfine-based atomic clocks [Prestage et al 1995]. The first laboratory attempt to search for a varying α set a (temporal) upper limit of $\sim 4 \times 10^{-14}$ per year for its variation. This technique has recently been used in a rubidium vs cesium fountain clock comparison [Marion et al, 2003], as well as the comparison of a cesium fountain with an optical mercury ion clock, where an optical transition in the ion was used [Bize et al, 2003]. These more recent experiments set the limit for a fractional time variation of $\alpha \leq 10^{-15}$/yr. This technique is the most sensitive of the laboratory searches for changing atomic constants. Recent results are shown in Table 1.

SCSO vs Cs hfs	$g_{Cs}\frac{m_e}{m_p}\alpha^{3.74}$	**<4x10^{-12}/yr**	**Turneaure et al (1976)**
Hg^+ vs H-Maser (hfs)	$\frac{\mu_{Hg}}{\mu_H}\alpha^{2.2}$	**<8x10^{-14}/yr**	**Prestage et al (1995)**
Rb vs Cs (hfs)	$\frac{\mu_{Rb}}{\mu_{Cs}}\alpha^{-0.44}$	**<7x10^{-16}/yr**	**Marion et al (2003)**
Optical Hg^+ vs Cs hfs	$g_{Cs}\left(\frac{m_e}{m_p}\right)\alpha^{6.0}$	**<7x10^{-15}/yr**	**Bize et al (2003)**

Table 1: Summary of recent clock comparisons and the combination of atomic constants tested for time variation.

Space Station Clock Comparisons:

Laser cooled atomic clocks and cryogenic cavity oscillators are planned for the ISS (International Space Station); a Cesium clock (PARCS) [Heavner 2001] with planned accuracy in the low 10^{-16} 's and later a Rubidium clock (RACE) [Fertig 2000] in the low 10^{-17} 's. These clocks will use the micro-gravity environment to increase the atomic line-Q and stability beyond Earth based fountain configurations. The cryogenic cavity oscillator (SUMO) [Lipa 2001], will be linked to one or both of the atomic clock experiments so that clock comparisons can be made in orbit. The clocks will be used to search for 'preferred frame' Lorentz violations of the sort

$$\frac{c(\theta)}{c} = 1 + (\frac{1}{2} - \beta + \delta)\frac{V^2 \sin^2(\theta)}{c^2} + (\beta - \alpha - 1)\frac{V^2}{c^2}$$

where *c(θ)* is the speed of light in the presumed preferred frame through which the clocks travel with speed *V*. One candidate frame would be the rest frame of the cosmic microwave background through which the solar system travels at ~ 377 km/sec. The orbiting space station will modulate this velocity at ±8km/sec every 45 minutes causing a synchronous, relative clock frequency change. The $\sin^2\theta$ term would be revealed in a Michelson-Morely experiment, while the isotropic term is of the Kennedy-Thorndike type.

By comparing to an equally accurate clock on Earth, ISS clocks will improve upon the gravitational redshift measurement of GP-A by 10-fold. The ISS clocks will be 100x more stable than the H-maser of GP-A but the ISS orbit is only ~ 10% of the altitude of GP-A.

ESA will also use the ISS for atomic clock comparisons in the ACES program where a laser-cooled cesium clock and an H-maser will be compared, similar to the PARCS program. [Laurent et al, 2003]

Deep Space EP Tests:

Figure 1 shows and compares the gravitational red-shift through the solar system together with some discrete near Earth values. For example, from the Earth's surface to the ISS the red-shift is about 4×10^{-11}. Similarly, there is a $\sim4\times10^{-10}$ redshift to the GP-A maximum altitude, 10,000 km. The eccentricity in the Earth's motion around the Sun ($e = 0.017$) leads to an annual change in the Solar gravitational red-shift on Earth of $\sim3\times10^{-10}$.

Clearly the largest red-shifts accessible to solar system measurements occur near the Sun where an enhancement of 4 orders of magnitude are possible as compared to low Earth orbit. Yet, with today's small ultra-stable ion clocks, mission costs for a small (~ 200kg) solar gravity explorer are comparable or even competitive with Earth orbit gravity missions and clearly much more adventurous. The technical problems of spacecraft survival during a near solar flyby were studied 30 years ago and judged to be feasible even then. Small ultra-stable atomic clocks are now under development suitable for a ~ 200 kg spacecraft including clock payload that could make profound advances in searching for EP violating scalar fields that both theory and experiment today suggest. The technology spin-off for this mission would be the development of ~1 kg atomic clocks with stability equal to current day H-masers, and in a space-worthy package. This would benefit GPS, deep space navigation and radio science, and future optical space interferometry, since maser quality standards are required for generating the highest stability optical coherent links [*Science*, to be published].

Atomic Clock Comparisons: α-variations converted to clock frequency differences

For alkali atoms, an expression for the hyperfine interval may be obtained, as follows:

$$A_s = \frac{8}{3}\alpha^2 g_I Z \frac{z^2}{n^{*3}}\left(1-\frac{d\Delta_n}{dn}\right)F(\alpha Z)(1-\delta)(1-\varepsilon)\frac{m_e}{m_p}R_\infty c.$$

Here, z is the net charge of the ion without the valence electron, and n* is the effective quantum number with $\Delta_n = n - n^*$, δ and ε are related to the corrections for finite size of the nucleus. The relativistic Casimir correction factor, $F(\alpha Z) = 3\left[\lambda\left(4\lambda^2 - 1\right)\right]^{-1}$, where $\lambda = \sqrt{1-(\alpha Z)^2}$, leads to the differential sensitivity in the alkali microwave hyperfine clock transition frequencies. The α-variation induced drift between two atomic hyperfine clocks with atomic numbers Z_A and Z_B is given by the following expression:

$$y_{AB} \equiv \frac{\delta f_A}{f_A} - \frac{\delta f_B}{f_B} = [L_d F(\alpha Z_A) - L_d F(\alpha Z_B)]\frac{\delta\alpha}{\alpha}$$

where $L_dF(\alpha Z)$ is the logarithmic derivative of the Casimir factor, plotted vs atomic number Z in Figure 2.

It is clear from the above equation that two atomic clocks with different Z display different frequency shifts following a variation of α. From Figure 2, we see that a given change of α will affect all clock pairs differently, allowing a unique signature to identify an α change.

The SpaceTime instrument thus consists of three clocks based on three different atomic species that can be inter-compared for individual signatures. To reduce the influence of systematic errors that can mimic our signal, the three clocks share the same environment. Thus the entire experiment is designed to provide a clean and unambiguous result, based on a technology that is proven, and has an outstanding chance for success. Finally, the spinning spacecraft, moving at 300 km/s, or 1/1000 of the speed of light, at its closest approach will test another important question with fundamental underpinning: Is Lorentz symmetry robust [Kostelecky, 1999], or does it fail at some measurable limit? This question is important since string theory, and theories that extend beyond the Standard Model result in physics without Lorentz and other global symmetries such as CPT.

Small Ion-Clock Payload:

The frequency of three atomic clocks based on hyperfine transitions of Hg^+ (Z=80), Cd^+ (Z=48), and Yb^+(Z=70) will be simultaneously monitored during a solar flyby to determine whether these different clocks will measure the same time interval near to and far from the Sun. A laboratory prototype Hg^+ clock has shown ultra-stable operation ($4\text{x}10^{-13}/\sqrt{\tau}$) in a ~ 3 liter package, far smaller than other clock technologies and represents the state of the art for small atomic clocks. Ions confined in electromagnetic traps undergo benign wall collisions and maintain quantum coherence over many seconds on the clock transition, routinely achieving line-Q's near 10^{12}. This technology is relatively simple since no lasers, cryogenics, or microwave cavities are used. Furthermore, because ions are trapped via rf electric fields, the clock does not depend upon micro-gravity to operate as do modern laser cooled neutral atom clocks.

The instrument for this mission is composed of three ion trap clocks in a package where much of the hardware and electronics is common to all three clocks. Some of the clock systematic frequency perturbations will be common to all three clocks and will have a characteristic signature that can be identified and removed from the difference of the clock frequencies, so that relative stability's to 10^{-16} in the inter-comparison can be reached. The local oscillator (LO) will simultaneously interrogate each of the three clock transitions thereby removing LO noise in the inter-comparison, and greatly improving short-term clock noise. Because ion-trap-based clocks are relatively immune to temperature and magnetic field changes, a simple, robust electronics package is sufficient for ultra-stable operation.

The tri-clock measurement offers a suppression of other common mode frequency shifts of the three atomic transitions. The suppression of systematic frequency pulling can be applied to the unknown variations of the solar magnetic field along the spacecraft (S/C) trajectory. A 1-G or more field variation might be expected during the solar flyby. This level of shielding is very difficult to achieve within the mass and power budget.

The magnetic sensitivity of the three hyperfine clock transitions is quadratic, $f = f_0 + \beta H_0^2$. The change of the clock frequency as the operating field changes by δH_0 is given by $\delta y \equiv \delta f/f_0 = 2\beta H_0 \delta H_0$ where the constant β describes the field sensitivity of each of the three clock transitions. Since $\beta \sim 1/f_0$, atoms with a smaller hyperfine splitting, f_0, shift more, unlike the sensitivity to a change in α as shown above.

The two simultaneous equations for the variation of the difference frequencies are

$$\delta y_{AB} = (L_d(\alpha Z_A) - L_d(\alpha Z_B))\ \delta\alpha/\alpha + (1-\beta_B f_A/\beta_A f_B)\ (2\beta_A/f_A)H_0\delta H/S$$
$$\delta y_{AC} = (L_d(\alpha Z_A) - L_d(\alpha Z_C))\ \delta\alpha/\alpha + (1-\beta_C f_A/\beta_A f_C)\ (2\beta_A/f_A)H_0\delta H/S;$$

S is the magnetic shielding factor for external field variations δH along the S/C trajectory, i.e., $\delta H_0 = \delta H/S$. For the hyperfine clock transitions in Hg, Cd, and Yb, these equations can be inverted to solve for $\delta\alpha/\alpha$ and $(2\beta_A/\nu_A)H_0\delta H/S$ along the trajectory of the near-Sun flyby. Thus, even with imperfect magnetic shielding and the accompanying clock frequency pulling, an unambiguous variation of α could be extracted.

Mission Design:

Figure 3 illustrates the entire interplanetary trajectory to the Sun including the gravity assist flyby at Jupiter. The time tics are 50-day intervals. The gravity assist flyby is used to: 1) cancel the trajectory angular momentum, allowing the S/C to fall into a 6-R_{Solar} perihelion, 2) rotate the plane of the heliocentric orbit to an 'over the solar pole' quadrature trajectory, timed so that the Sun-S/C-Earth angle = 90.0 degrees at perihelion. This latter condition is fundamental to the S/C architecture, which always has the shield pointed at the Sun and the high gain antenna (HGA) pointed at Earth.

The thermal shield for the S/C, as the S/C spins, maintains its orientation toward the Sun at all times protecting the sensitive elements from the extreme thermal environment. This is a passive attitude control technique that simplifies the control of the S/C and allows a very robust design in this otherwise hostile environment.

It is interesting to point out that the most challenging aspect of the mission, affecting orbital trajectory and the number of passes (single) by the Sun is the power requirements.

Because of the extreme heat encountered near the Sun, solar panels, even those designed for high temperature, cannot be used. Instead, a bank of batteries must provide the needed power to the spacecraft systems, and the instrument. The mass associated with the batteries ultimately limits the choices of a trajectory with a given launch vehicle, as well as the size of the S/C and associated systems. This ironic limitation (shortage of power while so near the Sun) is the major design issue that affects virtually all aspects of the mission.

Conclusions:

We have briefly discussed a mission design study based on the inter-comparison of the oscillation frequencies of three atomic clocks based on three different species of singly ionized atoms. By flying this instrument to within six solar radii of the sun it is possible to search for a variation of fine structure constant to a level that is not accessible to earth-based instruments. As briefly mentioned above, and discussed elsewhere in this volume the detail of theories that predict a temporal or spatial variation in fine structure constant, such as M-theory or theories based on varying c or e, are rather tentative. Experimental tests of these theories based on a search for varying α then must produce direct and unambiguous results to be most valuable. The three-clock comparison discussed here is indeed such an approach. As discussed above, each atomic clock will drift in a specific manner with varying α and inter-comparison of these variations assures that an observed signal produces a clear result. Secondly, the technology of atomic clocks is well developed, and a space test based on clocks has an inherently large probability of success.

With today's small ultra-stable ion clocks, mission costs for a small (~ 200kg) solar gravity explorer are comparable or even competitive with Earth orbit gravity missions and clearly much more adventurous. The technical problems of spacecraft survival during a near solar flyby were studied 30 years ago and judged to be feasible even then.

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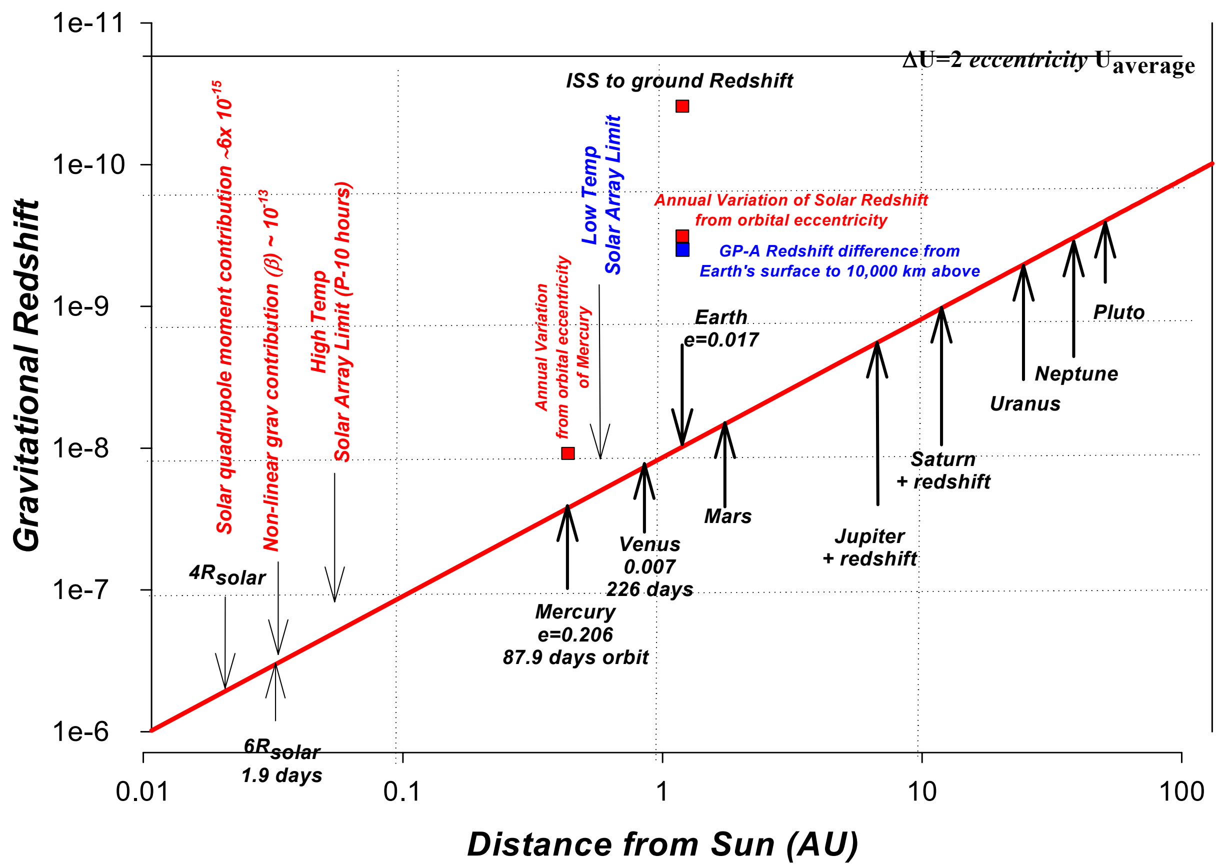

Figure 1. Solar gravitational red-shift throughout the solar system. Also shown at 1 AU is GP-A apogee and ISS red-shifts from s/c to the Earth surface.

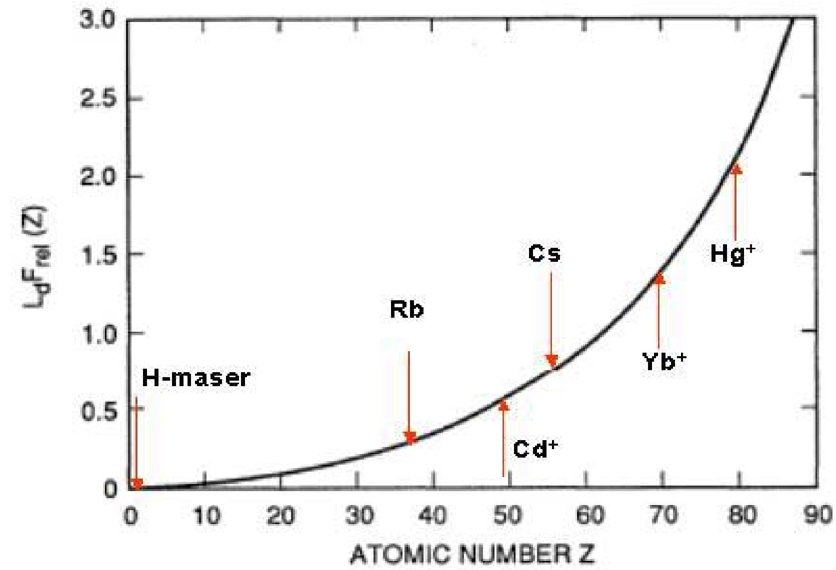

Figure 2. The logarithmic derivative of the Casimir factor. This derivative shows the fractional change in each atomic clock frequency due to a fractional change in the fine structure constant α.

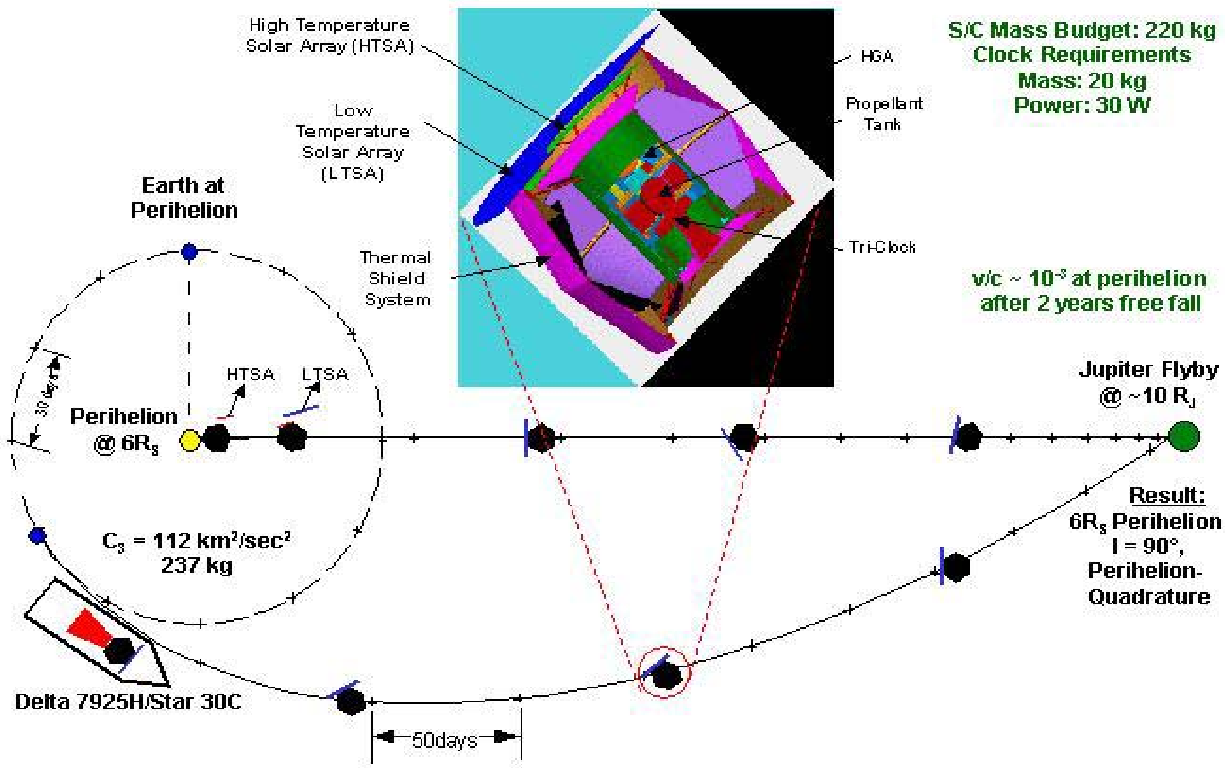

Figure 3. Spacecraft trajectory for 6-R_{Solar} flyby. A small s/c containing 3 atomic ion clocks would search for an Equivalence Principle violating scalar field that changes the fine structure constant, α, consequently pulling the relative clock frequencies.