\( \Delta \alpha / \alpha \) from QSO absorption lines driven by an oscillating scalar field

Yasunori Fujii\(^1\) and Shuntaro Mizuno\(^2\)

\(^1\) Advanced Research Institute for Science and Engineering, Waseda University, Tokyo, 169-8555 Japan
\(^2\) Department of Physics, Waseda University, Tokyo, 169-8555 Japan

Abstract

An oscillatory behavior of the scalar field supposed to be responsible for the cosmological acceleration appears to be seen better in the new result on the QSO absorption lines from VLT-UVES sample (case 1) than in the past reports on the time-variability of the fine-structure “constant” derived from the Keck/HIRES observation.

Many-multiplet method, which played a central role in the search of time-variability of the fine-structure “constant” \( \alpha \) from the Keck/HIRES data of QSO absorption lines [1,2], has been applied recently to the VLT-UVES sample, with the more restricted selection criteria [3,4]. The wavelengths of the lines have been determined by two different ways, using either laboratory wavelengths of Mg II, I and Si II lines with terrestrial isotopic abundances (case 1) or with those of the dominant isotopes (case 2) [3]. From the case 1, which the authors claim to be more robust, they report no evidence of the changing \( \alpha \), in contrast to the previous Keck/HIRES result. Despite the warning that more careful analysis on the likely systematic errors is necessary before final conclusion is reached [5], it should be worth trying to apply some of the theoretical analyses focusing on different features of the observations accepted at a face value for the time being, in order to provide hopefully a guide in entangling complications involved in the phenomenological analyses.

There has been a class of theoretical models in which a cosmological scalar field (dilaton or quintessence) shows itself through a time-dependent fine-structure constant [6-12]. In some of them the scalar field is expected even to be responsible for the cosmological acceleration [6-11].

On the cosmological side, the scalar field beyond the linearization regime is supposed generally to be trapped to a potential superimposed to a smooth background, like an exponential potential, thus causing nearly constant behavior of the sufficient amount of dark energy, the energy density of the scalar field acting as an effective cosmological “constant.” The trapping process entails \( \Delta \sigma \), a damped-oscillation-like behavior, as a function of the cosmic time \( t \), and hence of the fractional look-back time \( s = 1 - t/t_0 \) with \( t_0 \) the present age of the universe. We may also assume that the observed coupling strength is proportional to the scalar field, thus expecting \( y(s) = \Delta \alpha / \alpha \times 10^5 = K \Delta \sigma (s) \), with \( K \) a constant. An oscillatory behavior might provide an advantage in reconciling the size of \( \Delta \alpha / \alpha \) recently suggested by the QSO observations with the 2–3 orders of magnitude smaller value constrained by the Oklo phenomenon [13-15].

In view of the uncertainties both on the theoretical and the observational sides, we may follow a phenomenological approach to fit the observed \( \Delta \alpha / \alpha \) by the assumed simple damped oscillation for \( y(s) \), as was attempted in [8] applied to the measurement on the Keck/HIRES QSO absorption lines [1]. We assumed that the Oklo constraint corresponds to a zero of the oscillation at \( s_{\text{oklo}} = 0.142 \),\footnote{The Oklo constraint corresponds to a zero of the oscillation at \( s_{\text{oklo}} = 0.142 \).}
determining the other three parameters by best fitting the QSO data. We then found that the 3-
parameter fit is nearly as good as the weighted-mean-fit as far as the QSO result is concerned [8].

We now improve this fit by incorporating a zero also at $s = 0$, because $\Delta \alpha$ is the difference of $\alpha$
from today’s value and should vanish at $s = 0$ by definition. This condition is met by offsetting the
damped oscillation, as implemented [14] by
\[
y(s) = a \left( e^{bs} \cos(v_1) - \cos(v_1) \right),
\]
where $v/s = v_1/s_1 = v_{\text{oklo}}/s_{\text{oklo}} = 2\pi T^{-1}$ with $v_1$ determined by
\[
v_1 = \tan^{-1} \left( \frac{e^{-bs_{\text{oklo}}} - \cos(v_{\text{oklo}})}{\sin(v_{\text{oklo}})} \right),
\]
limiting ourselves to the behavior that allows many oscillations, at the moment. One easily checks
that $y(s)$ vanishes at $s = 0$ and $s = s_{\text{oklo}}$. The relaxation time $b^{-1}$ and the period $T$ are both
measured in units of $t_0$. We applied this to the more recent result of 143 data points of [2]. The
least reduced chi-squared $\chi^2_{\text{rd}} = 1.015$ was obtained for $a = 0.020, b = 5.5, T = 1.352$, as plotted in
Fig. 1. By comparing with their $\chi^2_{\text{rd}} = 1.023$ for the simple weighted mean, or the 1-parameter fit in
terms of a horizontal straight line $y = -0.573$, our fit is again nearly as good as theirs. We emphasize
that we have increased the number of the parameters from 1 to 3, plus 1 if we take fitting the Oklo
constraint at $s_{\text{oklo}}$ into account, based on a theoretical ground in connection with the cosmological
acceleration, not simply for a better fit, leaving the argument of the Bayesian information criterion
[16] not immediately to be applied.

We find that the preferred value of $T$ is much larger than $\sim 0.2$ expected from the “typical”
cosmological solutions which successfully account for the observed acceleration based on the two-scalar
model [7,8,17], though the second scalar field shows no oscillatory behavior of immediate relevance.
Such a small value of $T$ is entirely outside the confidence region of 68%, as shown in Fig. 2. We may
define the mass $m_\sigma = 2\pi/T$. The large and small $T$ mentioned above correspond to $m_\sigma/H_0 = 4.75$ and $\sim 32$, respectively.

To meet the feature of the “observed” broad distribution, large $T$ were chosen in [10], or small $m_\sigma/H_0 = 7.25$ or 3.24. They intended, moreover, to respect another constraint from the meteorite dating at $s \approx 0.33$ [18] by choosing rather large $b$, if interpreted in terms of (1), resulting in too much pronounced $|y|$ toward the high-$s$ end, thus against the observation. Nearly the same tendency is found in the analysis of [11] with $m_\sigma/H_0 \lesssim 3$. In our fit in Fig. 1, we ignored this constraint according to our own argument [19,20].

Quite different features appear, on the other hand, to emerge in the most recent report from the VLT-UVES group [3,4]. The result from 23 data points particularly in the case 1 is expressed as a weighted mean $y = -0.06 \pm 0.06$, with $\chi^2_{rd} = 0.95$, which may be interpreted as no evidence for time-dependence of $\alpha$, contrary to the Keck/HIRES result [1,2]. We attempted, however, the same type of fit in terms of an offset damped oscillator as in (1). By transforming the data originally expressed in terms of redshift, $z$, into a function of $s$ assuming spatially flat Friedmann cosmology with $t_0 = 13.78$ Gy, $h = 0.70, \Omega_\Lambda = 0.7$, we found the least $\chi^2_{rd} = 0.53$ for $a = -0.050, b = 3.1, T = 0.134$, as illustrated in Fig. 3, together with Fig. 4 for the 68% confidence region. Surprisingly, this chi-squared is even smaller than 0.95 for the weighted mean. We point out that the presence of oscillation is already obvious by a “visual” inspection of Fig. 3 with the fitted curve removed.

![Figure 3](image1.png)  
**Figure 3**: The best fit to the QSO data for case 1 in [3,4]. The portion of the curve for $s < 0.2$ is magnified by 2.5 times. The dotted-dashed line is for the weighted mean, the 1-parameter fit in terms of a horizontal straight line $y = -0.06$, with $\chi^2_{rd} = 0.95$, compared with which our 0.53 appears even improved.

![Figure 4](image2.png)  
**Figure 4**: Confidence volume of 68% of the fit in Fig. 3, represented in the same manner as in Fig. 2. Notice $a$ is now negative.

The difference 0.42 in $\chi^2_{rd}$ implies the $p$-value (in the goodness-of-fit test) improved by $\sim 45\%$, a significant amount even for the small degrees of freedom 23–3=20. We might say that the VLT-UVES data for the case 1 allows a nonzero oscillating $\alpha$, despite an apparently null result which can be derived from the simple weighted mean. Furthermore the favored value of $T$ turns out to be “small,” though somewhat even smaller than $\sim 0.2$ expected typically from the two-scalar model, showing obviously a pattern significantly different from “broad” distribution characterizing the Keck/HIRES result. Note also that the fitted curve crosses another zero below $s_{oklo}$, and that $\dot{\alpha}/\alpha$ evaluated at
present \((s = 0)\) is entirely different from what we infer from the QSO result by a linear approximation.

We discovered several other fits with \(\chi^2_{\text{rd}}\) larger than the smallest value 0.527 as shown in Fig. 3, still considerably smaller than 0.95 for the weighted mean. Only two examples are mentioned here; \(a = -0.000352, b = 10.0, T = 0.156, \chi^2_{\text{rd}} = 0.590\) and \(a = 0.156, b = 1.0, T = 0.253, \chi^2_{\text{rd}} = 0.777\). We may expect that wide variety of the cosmological solutions will be selected as more accurate results of \(\Delta \alpha/\alpha\) become available in the future.

We also notice that VLT-UVES result includes the analysis of some sub-samples, giving still smaller chi-squared. We focused on the 12 absorption systems listed in the first line of Table 5 of [3] for “single + double (case 1),” applying the same fit as for the full sample. The set of parameters, \(a = -0.066, b = 2.55, T = 0.134\), yields the minimized \(\chi^2_{\text{rd}} = 0.337\) again smaller than 0.552 for the weighted mean, \(y = -0.077 \pm 0.101\). The curve of the fit looks nearly the same as in Fig. 3. This result seems to demonstrate how robust the presence of an oscillation is.

Having focused on the case 1, claimed to be robust most probably, we now apply the same analysis to the case 2. The weighted mean gives \(y = -0.36 \pm 0.06\) with \(\chi^2_{\text{rd}} = 1.03\). This case turns out more like the Keck/HIRES result; a negative \(y\) off the zero by 6 sigmas, and apparently broad distribution shown in the damped oscillation fit with \(a = 0.307, b = 0, T = 0.889\), as illustrated in Fig. 5, entailing \(\chi^2_{\text{rd}} = 0.91\) only slightly smaller than that for the weighted mean. Note that \(b = 0\) does not correspond to the absolute minimum of chi-squared, only at the physical boundary \(b \geq 0\). The fits with \(a > 0\) result in much larger chi-squared, close to \(\chi^2_{\text{rd}} = 2.52\) for the assumed null result.

It is interesting to note that the presence of mass \(m_{\sigma}\) does not prevent \(\sigma(t)\) from falling off smoothly, as seen in Fig. 5.8 of [7], Fig. 1 of [8] or Fig. 2 of [17]. This represents another mechanism not to disturb the global structure by a much larger mass of \(\sigma\) arising from the self-mass which makes the scalar force of finite-range of the macroscopic order of magnitude [21], hence leaving detection of possible WEP violation more remote [7].

We finally add that there is an even simplified version of the two-scalar model [7,17] obtained by removing the second scalar field [22], though the latter lacks the aesthetic advantage of the former in which no eternal inflation ensues. The scalar field continues to fall overriding maxima of the sine-Gordon potential included in addition to the background exponential potential until it is finally
trapped to one of the minima. Unlike in the two-scalar model, a mini-inflation, as shown in the upper panel of Fig. 6 with $\Omega_\Lambda$ passing through 0.7, occurs only with a smooth change of the scalar field, as illustrated in the lower panel. We failed to detect any oscillation even with the vertical scale magnified nearly by 2 orders of magnitude larger than in Fig. 5.10 of [7], Fig. 2 of [8] or Fig. 4 of [17], exhibiting a generic oscillation for the typical solution in the two-scalar model. This choice, which provides an exception to a conventional view on trapping associated with oscillation, might be favored if the future observations disprove oscillatory $\Delta\alpha/\alpha$ and if consistency between QSO and Oklo is achieved by other means. Still the universe will finally enter the eternal inflation basically as in [10,11].

![Figure 6: A solution in the one-scalar model [22] with the potential $V(\sigma) = e^{-45\sigma}[\Lambda + m^4(1 + \cos(\kappa \sigma))]$, where $\zeta = 1.5, \Lambda = 6.0 \times 10^{-4}, m = 0.8, \kappa = 0.351$ in the reduced Planckian units. The scalar field $\sigma$ varies only smoothly (in the lower panel) near the present time $\log t \approx 60$ corresponding to $t \approx 10^{10}$ y, at which $\Omega_\Lambda$ passes through $\sim 0.7$ (in the upper panel), hence causing acceleration of the universe.]

We would like to thank Bruce Bassett, Aldo Fiorenzano, Takashi Ishikawa, Akira Iwamoto, Nobuyuki Kanda, Kei-ichi Maeda, Michael Murphy and Naoshi Sugiyama for many useful discussions. Special thanks of one of the authors (Y.F.) are also due to Raghunathan Srianand for his generous help in understanding some details of the data.

References

[1] M.T. Murphy, J.K. Webb, and V.V. Flambaum, MNRAS, 345 (2003) 609.

[2] M.T. Murphy, V.V. Flambaum, J.K. Webb, V.V. Dzuba, J.X. Prochaska, and A.M. Wolfe, astro-ph/0310318.

[3] H. Chand, R. Srianand, P. Petitjean, and B. Aracil, astro-ph/0401094.

[4] R. Srianand, H. Chand, P. Petitjean, and B. Aracil, astro-ph/0402177.

[5] L. Cowie and A. Songaila, Nature 428 (2004) 132.
[6] Y. Fujii, Int J. Mod. Phys. D11 (2002) 1137, First ASTROD School and Symp, 13–23 Sep 2001, Beijing, astro-ph/0204069; Astrophys. Space Sci, 283 (2003), 559, Proc. JENAM 2002, Porto, Portugal, 3–5 Sep 2002, gr-qc/0212019.

[7] Y. Fujii and K. Maeda, The scalar-tensor theory of gravitation, Cambridge University Press, 2003.

[8] Y. Fujii, Phys. Lett. B573 (2003) 39.

[9] C. Wetterich, Phys. Lett. B561 (2003) 10; M.C. Bento, O. Bertolami and N.M.C. Santos, astro-ph/0402159.

[10] L. Anchordoqui and H. Goldberg, Phys. Rev. D68 (2003) 083513.

[11] C.L. Gardner, Phys. Rev. D68 (2003) 043513.

[12] T. Chiba and K. Khor, Prog. Theor. Phys. 107 (2002) 631; D. Parkinson, B.A. Bassett and J.D. Barrow, Phys. Lett. B578 (2004) 235; D.F. Mota and J.D. Barrow, astro-ph/0309273; N.J. Nunes and J.E. Lidsey, astro-ph/0310882; P.P. Avelino, C.J.A.P. Martins and J.C.R.E. Oliveira, astro-ph/0402379.

[13] A.I. Shlyakhter, Nature 264 (1976) 340; physics/0307023; T. Damour and F. Dyson, Nucl. Phys. B480 (1996) 37; Y. Fujii, A. Iwamoto, T. Fukahori, T. Ohnuki, M. Nakagawa, H. Hidaka, Y. Oura, and P. Möller, Nucl. Phys. B573 (2000) 377; hep-ph/0205206.

[14] Y. Fujii, Proc. Astrophysics, Clocks and Fundamental Constants, 16–18 June 2003, Bad Honnef, Lecture Notes in Physics, to be published, hep-ph/0311026.

[15] S.K. Lamoreaux, nucl-th/0309048.

[16] A. Liddle, astro-ph/0401198.

[17] Y. Fujii, Phys. Rev. D62 (2000) 064004.

[18] K. Olive, M. Pospelov, Y.-Z. Qian, A. Coc, M. Cassé, and E. Vangioni-Flam, Phys. Rev. D66 (2002) 045022.

[19] Y. Fujii and A. Iwamoto, Phys. Rev. Lett. 91 (2003) 261101.

[20] K. Olive, M. Pospelov, Y.-Z. Qian, G. Manlhés, E. Vangioni-Flam, A. Coc, and M. Cassé, Phys. Rev. D (to be published), astro-ph/0309252.

[21] Y. Fujii, Prog. Theor. Phys. 110 (2003) 433.

[22] S. Dodelson, M. Kaplinghat and E. Stewart, Phys. Rev. Lett. 85 (2000), 5276.