Quintessence Cosmology and Varying $\alpha$

Takeshi Chiba $^a$ and Kazunori Kohri $^b$

$^a$ Department of Physics, Kyoto University, Kyoto 606-8502, Japan
$^b$ Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, 606-8502
Japan

(Received )

If the reported measurements of the time variation of the fine structure constant from observations of distant QSOs are correct, combined with the Oklo limit they would strongly constrain the class of the quintessence potential. If these results prove valid, future satellite experiment (STEP) should measure the induced violation of the weak equivalence principle. Future cosmological observations of nearby ($z < \sim 0.5$) absorption systems would make it clear whether the variation is significant or not.

1. Introduction. The Universe is filled with dark energy. If dark energy is dynamical, its dynamics is described by an ultra-light scalar field with mass $< \sim H_0$, called “quintessence”. Such a field could interact with ordinary matter, unless forbidden by symmetries. Because this field would be dynamical and the exchange of light fields gives rise to long range forces, the interaction of the field with ordinary matter would result in the time variation of the constants of nature over cosmological time scales and the violation of the weak equivalence principle. Since those effects have not been observed, such direct couplings were believed to be strongly suppressed.

Recently, however, observations of a number of absorption systems in the spectra of distant quasars indicate a smaller value of $\alpha$ in the past, and an optical sample exhibits a $4\sigma$ deviation for $0.5 < z < 3.5$: $\Delta\alpha/\alpha = (-0.72 \pm 0.18) \times 10^{-5}$. On the other hand, the severest limit on $\dot{\alpha}$ obtained from analysis of the isotope abundances in the Oklo natural reactor operated 1.8 Gyr ago is $|\Delta\alpha|/\alpha \lesssim 10^{-7}$. Are these data compatible?

In this paper, we elucidate the discrepancy between the QSO data and the Oklo limit and then point out the potential significance of these data in constraining a model of quintessence. We also estimate the degree of the violation of the equivalence principle to motivate future experimental precision tests of the equivalence principle.

While we were preparing this paper for the submission, we became aware of two related papers. Reference investigates a fifth force-type long range interaction mediated by a scalar field. Reference studies a model with a large coupling between non-baryonic dark matter and a scalar field.

2. QSO, Oklo, and Quintessence. From the perspective of an effective theory, no couplings of the quintessence field to ordinary matter should be ignored, unless they are forbidden by symmetry. Therefore, we expect, for example, the
coupling between $\phi$ and the photon

$$f(\phi)F_{\mu\nu}F^{\mu\nu},$$

(0.1)

where $f(\phi)$ is a function of $\phi$. Therefore the fine structure constant becomes a function of $\phi$: $\alpha = \alpha(\phi)$. We may expand $\alpha(\phi)$ about the present value $\phi_{\text{now}}$ assuming $\phi - \phi_{\text{now}} < M_{\text{pl}}$.

$$\alpha(\phi) = \alpha_{\text{now}} + \lambda \left( \frac{\phi - \phi_{\text{now}}}{M_{\text{pl}}} \right) + \ldots,$$

(0.2)

If no symmetry is imposed, the variation of $\alpha$ with $\phi$ is generally written to the leading order in $\phi/M_{\text{pl}}$ as

$$\frac{\Delta \alpha}{\alpha} \simeq \frac{\lambda \Delta \phi}{\alpha_0 M_{\text{pl}}},$$

(0.3)

where $\Delta \phi \equiv \phi_{\text{then}} - \phi_{\text{now}}$, and $\phi_{\text{then}}$ denotes the value of $\phi$ at that time. Observational evidence indicates $\Delta \alpha/\alpha \simeq -10^{-5}$ for $0.5 < z < 3.5$, which in turn implies

$$\lambda \left( \frac{\Delta \phi}{M_{\text{pl}}} \right) \simeq -10^{-7}.$$

(0.4)

---

* We note that due to the approximate global symmetry $\phi \rightarrow \phi + \text{const.}$, the only possible coupling of quintessence axion to a photon is of the form, $\phi F \tilde{F}$, and hence a $\phi FF$-type coupling is absent. Therefore the QSO data cannot be explained by quintessence axion.

** We note, however, that generically $\phi \sim M_{\text{pl}}$ for quintessence since $V'' \simeq H_0^2$. Hence this assumption is barely valid.
Such time variation can be explained for a wide class of quintessential potentials. An example is shown in Fig. 1 for the inverse power-law potential $\propto \phi^{-2}$ with $\Omega_M = 0.3$ and $h = 0.65$.

We also plot the datum from the Oklo phenomenon. The Oklo natural reactor that operated about 1.8 billion years ago in Oklo, Gabon corresponding to $z \simeq 0.13$ yields a bound of $\Delta \phi/\phi = (-0.9 \sim 1.2) \times 10^{-7}$ or $(-6.7 \sim 5.0) \times 10^{-17} \text{yr}^{-1}$. Using new samples that were carefully collected to minimize natural contamination with a careful temperature estimate of the reactors, Fujii et al. derived the bound $(-0.36 \sim 1.44) \times 10^{-8}$ or $(-0.2 \pm 0.8) \times 10^{-17} \text{yr}^{-1}$. These bounds imply

$$\lambda \left( \frac{\Delta \phi}{M_{pl}} \right) \lesssim 10^{-9} \sim 10^{-10}. \quad (0.5)$$

In Fig. 2 the required changes of $\phi$ are exhibited as functions of $z$, where we have adopted the conservative bound of Damour and Dyson. Figure 2 shows that the (absolute) value of $\phi$ must have decreased by more than two orders of magnitude only recently, $z \lesssim 1$. It is noted, however, that the Oklo bound is not cosmological but geophysical in nature, and assigning to the Oklo event the “cosmological redshift” $z \simeq 0.13$ may not be justified. For this reason, other cosmological observations of nearby absorption systems ($z \lesssim 0.5$) are required to verify or contradict such a conclusion. The current result is consistent with a null result.

The two relations in Eqs. (0.4) and (0.5) imply that the scalar field stopped evolving abruptly after $z \simeq 1$. Therefore, if we interpret the recent QSO data and the Oklo naively and attempt to explain them in terms of quintessence coupling to a photon, then we are led to a model in which a potential has a local minimum into which the scalar field was trapped only recently ($z \lesssim 1$), which would require a fine-tuning of model parameters, or to a model with a large coupling between non-baryonic dark matter and the scalar field. Examples are the Albrecht-Skordis model, the Barreiro-Copeland-Nunes model, and supergravity-inspired models, to name a few.

**Equivalence Principle.** The direct coupling of the form in Eq. (0.1) induces a violation of the weak coupling principle because the baryon mass is then a function of $\phi$. The degree of violation of the equivalence principle may be estimated in the manner of Ref. (5). (The details of this calculation appear in the Appendix.) Changing $\alpha$ causes a change in the nucleon mass coming from electromagnetic radiative corrections and hence results in a composite-dependence in free-fall experiments. The conventional Eötvös parameter $\eta$, which measures the difference between the accelerations of two test bodies, is estimated to be

$$\eta \sim 10^{-17} \left( \frac{\lambda}{3 \times 10^{-7}} \right)^2. \quad (0.6)$$

This value is much smaller than the present upper bound given by Eötvös-Dicke-Braginsky type experiments, $\eta < 10^{-13}$, and is therefore consistent with this
Fig. 2. $\lambda \Delta \phi$ as a function of $z$. The histogram represents the QSO data of Webb et al. Errors are represented by dotted lines. The arrow indicates the upper limit from the Oklo data. $\Delta \phi = \phi_{\text{then}} - \phi_{\text{now}}$. This figure shows clearly that $\phi$ must have stopped evolving abruptly only recently, $z < 1$.

3. Summary. Assuming that dark energy is an ultra-light scalar field (or "quintessence"), we have obtained quantitative results for the required cosmological change of the scalar field to account for both the recent QSOs data and the Oklo datum. If the reported measurements of nonzero $\Delta \alpha/\alpha$ are correct, combined with the Oklo limit, they would strongly constrain the class of quintessence potential. If these QSOs observations prove valid, the proposed satellite experiment for testing the equivalence principle (STEP) should be able to detect the violation of the weak equivalence principle induced by a scalar force mediated by quintessence. Because of the geophysical nature of the Oklo bound, its validity with respect to the present problem is suspect, and it is hoped that future cosmological observations of nearby ($z \lesssim 0.5$) absorption systems may clarify the situation.

Noted added: The great difficulty of explaining the observed time variation of the fine structure constant from the viewpoint of particle physics is discussed in the recent work Ref. 20: the induced variation in the vacuum energy would be enormously large. However, this may be nothing but the aspect of the problem of the cosmological constant: how the vacuum energy gravitates.
Acknowledgements

T. C. was supported in part by a Grant-in-Aid for Scientific Research (No. 13740154) from the Japan Society for the Promotion of Science.

Appendix

In this appendix, we calculate the degree of violation of the weak equivalence principle induced by varying $\alpha$ following the approach of Ref. [5].

The modification of the nucleon mass results from the electromagnetic radiative corrections. The leading order of the correction of proton and neutron masses is represented by [18]

$$\delta m_i = \frac{\Delta \alpha}{\alpha}, \quad \text{(A.1)}$$

where “$i$” is $p$ for the proton and $n$ for neutron, and

$$\delta \tilde{m}_p \simeq 0.63 \text{ MeV}, \quad \text{(A.2)}$$
$$\delta \tilde{m}_n \simeq -0.13 \text{ MeV}. \quad \text{(A.3)}$$

In this situation, the nucleon mass $m_i$ is not constant, but depends on $\phi$. Then, the nucleon-$\phi$ coupling induces the effective Yukawa interaction

$$\mathcal{L}_{\text{int}} = m_i(\phi) \overline{N}_i N_i = g_i \phi \overline{N}_i N_i, \quad \text{(A.4)}$$

where $N_i$ represents the spinor of nucleon “$i$”. Using Eq. (0.3), the coupling constant $g_i$ is given by

$$g_i = \frac{\delta \tilde{m}_i \lambda}{\alpha_0 M_{pl}}. \quad \text{(A.5)}$$

Therefore, the exchange of $\phi$ induces an extraordinary scattering among nucleons and leads to the Yukawa potential

$$V(r) = -\sum_i \sum_j \frac{g_i g_j}{4\pi} \frac{1}{r} e^{-m_\phi r} n_i^E n_j, \quad \text{(A.6)}$$

where $r$ is the distance between the Earth and the test body, $m_\phi$ is the mass of $\phi$, and $n_i^E$ ($n_j$) is the number of the nucleons in the Earth (test body). These couplings depend on the nucleon species, which leads to the violation of the equivalence principle. Because the mass of $\phi$ is minuscule ($m_\phi \sim H_0$), we limit our consideration to the following shape of the potential in this study:

$$V(r) = -\sum_i \sum_j \frac{g_i g_j}{4\pi} \frac{1}{r} n_i^E n_j, \quad \text{for } r \ll \frac{1}{m_\phi} \sim H_0^{-1}. \quad \text{(A.7)}$$

The acceleration induced by the $\phi$-exchange force is given by

$$a_\phi = \frac{1}{m} \frac{dV(r)}{dr}. \quad \text{(A.8)}$$
where \( m \) is the mass of the test body. On the other hand, the usual Newtonian acceleration is given by

\[
a_g = \frac{M_E}{M_p^2 r^2},
\]

(A-9)

with the mass of the Earth \( M_E \). Then, the total acceleration is given by

\[
a = a_\phi + a_g.
\]

(A-10)

It is convenient to introduce the following parameter to study the difference between the accelerations of two test bodies in Eötvös-Dicke-Braginsky-type experiment:

\[
\eta = \frac{2|a_1 - a_2|}{|a_1 + a_2|}.
\]

(A-11)

Here \( a_1 \) and \( a_2 \) are the accelerations of the two bodies. We assume that the test bodies have almost equal masses, \( m_1 \simeq m_2 \), i.e., \( n_{n,1} + n_{p,1} \simeq n_{n,2} + n_{p,2} \). In addition, we assume that \( m = (n_n + n_p)\overline{m} \) and \( M_E = (n_n^E + n_p^E)\overline{m} \), where \( \overline{m} \) denotes the atomic mass unit (\( \simeq 0.931 \) MeV). Then, for relatively small \( \lambda (\ll \mathcal{O}(10)) \), we find

\[
\eta \simeq \frac{\lambda^2}{4\pi\alpha_0^2 \overline{m}^2} \left( R_n^E \delta \tilde{m}_n + R_p^E \delta \tilde{m}_p \right) \left( \Delta R_n \delta \tilde{m}_n + \Delta R_p \delta \tilde{m}_p \right),
\]

(A-12)

where we have defined the nucleon-number fraction in the Earth as \( R_n^E \equiv n_n^E / (n_n^E + n_p^E) \) and the difference of the nucleon-number fraction of the test bodies as \( \Delta R_i \equiv |n_{i,1} - n_{i,2}| / (n_n + n_p) \). For the sake of simplicity, we assume that \( R_n^E \simeq R_p^E \simeq 0.5 \). In Ref.\[5\] the relation \( \Delta R_n \sim \Delta R_p \sim 0.06 - 0.1 \) is estimated for typical materials used in experiments (copper, lead and uranium). Adopting the above values, we find

\[
\eta \sim 10^{-4} \lambda^2.
\]

(A-13)

---

[1] Recent experimental constraints on \( \dot{\alpha} \) and \( \dot{G} \) are reviewed in, T. Chiba, arXiv:gr-qc/0110118 in the proceedings of Frontier of Cosmology and Gravitation.

2 S. M. Carroll, Phys. Rev. Lett. 81, 3067 (1998).

3 T. Chiba, Phys. Rev. D 60, 083508 (1999).

4 J. K. Webb et al., Phys. Rev. Lett. 87, 091301 (2001).

5 G. R. Dvali and M. Zaldarriaga, arXiv:hep-ph/0108217.

6 K. A. Olive and M. Pospelov, arXiv:hep-ph/0110377.

7 D. B. Kaplan, Nucl. Phys. B 260, 215 (1985); M. Srednicki, Nucl. Phys. B 260, 689 (1985).

8 T. Damour and F. Dyson, Nucl. Phys. B 480, 37 (1996).

9 Y. Fujii, A. Iwamoto, T. Fukahori, T. Ohnuki, M. Nakagawa, H. Hikida, Y. Oura and P. Möller, Nucl. Phys. B 573, 377 (2000).

10 J.D. Barrow and C. O’Toole, MNRAS 322, 585 (2001).

11 C. L. Carilli et al., Phys. Rev. Lett. 85, 5511 (2000).

12 A. Albrecht and C. Skordis, Phys. Rev. Lett. 84, 2076 (2000).

13 T. Barreiro, E. J. Copeland and N. J. Nunes, Phys. Rev. D 61, 127301 (2000).
[14] E. J. Copeland, N. J. Nunes and F. Rosati, Phys. Rev. D 62, 123503 (2000).
[15] P. Brax, J. Martin and A. Riazuelo, Phys. Rev. D 64, 083505 (2001).
[16] S. Baessler et al., Phys. Rev. Lett. 83, 3585 (1999).
[17] http://einstein.stanford.edu/STEP/.
[18] J. Gasser and H. Leutwyler, Phys. Rept. 87, 77 (1982).
[19] R. V. Eötvös, D. Pekar and E. Fekete, Annalen Phys. 68, 11 (1922); P. G. Roll, R. Krotkov and R. H. Dicke, Annals Phys. 26, 442 (1964); V.B. Braginsky and V.I. Panov, Sov. Phys. JETP 34, 463 (1972).
[20] T. Banks, M. Dine, and M.R. Douglas. hep-ph/0112059.