TIME VARIATION OF FUNDAMENTAL CONSTANTS AS A PROBE OF NEW PHYSICS

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Time variation of fundamental constants would not be surprising in the framework of theories involving extra dimensions. The variation of any one constant is likely to be correlated with variations of others in a pattern that is diagnostic of the underlying physics.

1. Introduction

There has recently been reported evidence for a possible time variation of the fine structure constant on cosmological time scales \(^1\). Such variations are not surprising in any theoretical framework for the unification of basic forces involving extra dimensions or in which dimensionless couplings are related to the expectation values of scalar fields. However, the variation of \(\alpha\) is likely to be correlated with the variations in other fundamental quantities, such as other gauge and Yukawa couplings, and the ratios of such dimensionful scales as the unification and electroweak or supersymmetry-breaking scales, or the unification and gravity scales. Thus, the observation of such variations is a powerful probe of the underlying physics. I briefly summarize the relevant issues and describe an analysis and parametrization of these effects done in collaboration with Matt Strassler and Gino Segrè \(^2\).

2. Theoretical motivations

There have been speculations going back to the pioneering work of Dirac in 1937 that the fundamental “constants” of nature may vary in time \(^3,4,5,6,7\). From a modern perspective, time-variation is not surprising. For example,
in superstring theories and many brane-world scenarios, couplings are associated with moduli (scalar fields), which could be time-varying. In fact, time variation could be expected in any theory in which some or all of the couplings are associated with the expectation values of scalar fields, provided that they vary on cosmological time scales. In the standard model, for example, masses are proportional to the expectation value of the Higgs field. Gauge and Yukawa couplings can similarly be associated with the expectation values of scalar fields that occur in higher-dimensional operators.

As a simple example, suppose there is a higher-dimensional operator coupling a scalar $\phi$ to the electromagnetic tensor $F_{\mu\nu}$,

$$\mathcal{L}_{elm} \sim \frac{1}{4} \left[ 1 + \frac{\lambda \phi}{M_{\text{PL}}} \right] F_{\mu\nu} F^{\mu\nu} + \cdots,$$

(1)

where $\lambda$ is dimensionless and $M_{\text{PL}}$ is the Planck scale. It is useful to then replace $A_\mu$ by $A'_\mu$, where

$$A_\mu = A'_\mu \left( 1 - \frac{\lambda \phi}{2M_{\text{PL}}} \right),$$

(2)

so that $A'_\mu$ has a canonical kinetic energy. The couplings of charged particles to $A'_\mu$ will then be canonical in terms of a rescaled electric charge $e'$, related by

$$e = e' \left( 1 + \frac{\lambda \phi}{2M_{\text{PL}}} \right).$$

(3)

e' is universal, i.e., the rescaling is the same for all charged particles. If $\phi$ were a constant classical field, then the effects of these rescalings would be unobservable. However, if $\phi$ varies with time or in space, the effective electric charge $e'$ would also vary. For example, if $\phi$ is time dependent, it would satisfy

$$\ddot{\phi} + 3H \dot{\phi} + \frac{\partial V}{\partial \phi} = 0,$$

(4)

where $H$ is the Hubble expansion rate and $V$ is the scalar potential.

$\phi$ could be associated with a field introduced for other purposes, e.g., quintessence, or it might have no other cosmological significance (i.e., $\phi$ might or might not contribute significantly to $H$).

In addition to the time/space variation, there would be new operators associated with the derivatives of $\phi$, which are usually assumed to be small for small variations. There would also be new long-range forces

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coupling to electromagnetic energy density mediated by the quantum of $\phi$. These would violate the equivalence principle and could lead to strong but model-dependent bounds \textsuperscript{13,10}.

One objection to the notion of time varying couplings is that in many frameworks the natural scale for the rate of variation of, e.g., the fine structure constant $\alpha$, might be expected to be

$$\dot{\alpha}/\alpha \sim M_{PL} \sim 10^{+43}s^{-1}, \quad (5)$$

while any actual variation is clearly very much smaller than this\textsuperscript{c}. For example, the Webb et al. results suggest

$$\dot{\alpha}/\alpha \sim 10^{-15}yr^{-1} \sim 10^{-66} M_{PL}. \quad (6)$$

It is tempting to assume that since $\dot{\alpha}/\alpha$ is so small compared to its natural scale it must be exactly zero or at least unobservably small for some reason. However, it is worth considering an analogy with the cosmological constant: in most frameworks the natural scale for the vacuum energy density, related to the cosmological constant by $\rho_{vac} = \Lambda_{\text{cosm}}/8\pi G N$, is $\rho_{vac} \sim M_{PL}^4$. Most people assumed that since $\rho_{vac}$ is so much smaller than this, there must be some principle to ensure $\rho_{vac} = 0$. Recently, however, the Type IA supernova and CMB data have independently indicated that

$$\rho_{vac} \sim 10^{-124} M_{PL}^4 \neq 0. \quad (7)$$

(The observed dark energy may not be a true cosmological constant. It could be a time-varying quantity such as quintessence. For the purposes of this remark it does not make any difference.)

If $\alpha$ does vary with time, then it is likely that other fundamental constants, such as other gauge couplings $\alpha_i$, Yukawa couplings $h$, the electroweak scale $v$, and the Newton constant $G_N = 1/M_{PL}^2$ also vary in a correlated way \textsuperscript{2,4,14,15}. The relation of these quantities is presumably specified in any complete unified description of nature, though the form of the relations depends on the theory. One should therefore allow for the possibility that other quantities are varying when interpreting the observational data. Observations (or non-observations) of time or space variations can therefore be viewed as a probe of the underlying physics and how the various quantities are related.

\textsuperscript{c}This is reminiscent of the flatness problem, expressed as the statement that the natural time scale for the evolution of the universe is $1/M_{PL}$ rather than $1.4 \times 10^{10}$ yr.

\textsuperscript{d}I will take the view that only dimensionless couplings and ratios of mass scales are physically meaningful, and that quantities such as $\hbar$ and $c$ are derived quantities rather than fundamental. In that case, they can be taken to be fixed at unity. For a debate on such matters, see \textsuperscript{16}. 


3. Search for varying $\alpha$

Webb et al.\(^1\) have studied the absorption of light from background quasars by molecular clouds in the redshift range $0.5 < z < 3.5$. They apply a new “many multiplet” method to simultaneously study many relativistic (i.e., $O(\alpha^2, \alpha^4)$) splittings, obtaining evidence for an increase in $\alpha$,

$$\Delta \frac{\alpha}{\alpha} = \frac{\alpha_z - \alpha_0}{\alpha} = -(0.72 \pm 0.18) \times 10^{-5}, \quad \text{(8)}$$

where $\alpha_z$ ($\alpha$) refers to the fine structure constant at redshift $z$ (at present). This would correspond to $\dot{\alpha}/\alpha \sim 10^{-15}/\text{yr}$ for $\dot{\alpha}/\alpha = \text{constant}$. Using a different method, Bahcall et al.\(^{17}\) find a result consistent with no variation, though with lower precision, $\Delta \frac{\alpha}{\alpha} = (-2 \pm 1.2) \times 10^{-4}$, for the redshift range $0.16-0.80$. Similarly, Cowie and Songaila\(^{18}\) constrain $X \equiv \frac{\alpha^2 g_p m_e}{M_p}$, from the 21 cm hyperfine line in hydrogen at $z \sim 1.8$, and Potekhin et al.\(^{19}\) limit $Y \equiv \frac{M_p}{m_e}$ from molecular hydrogen clouds at $z = 2.81$:

$$\Delta \frac{X}{X} = (0.7 \pm 1.1) \times 10^{-5}, \quad \Delta \frac{Y}{Y} = (8.3^{+6.6}_{-5.0}) \times 10^{-5}. \quad \text{(9)}$$

There are also stringent laboratory limits. For example, Prestage et al. obtain\(^20\) $|\Delta \frac{\alpha}{\alpha}| < 1.4 \times 10^{-14}$ over 140 days, corresponding to $\dot{\alpha}/\alpha < 3.7 \times 10^{-14}/\text{yr}$ if constant. More recently, Sortais et al. obtained\(^{21}\) $\dot{\alpha}/\alpha < (4.2 \pm 6.9) \times 10^{-15}/\text{yr}$. Laboratory techniques may ultimately be sensitive to $\dot{\alpha}/\alpha < 10^{-18}/T$, where $T$ is the running time\(^5\).

A very stringent limit comes from the OKLO natural reactor\(^5\). In particular, the $^{149}\text{Sm}/^{147}\text{Sm}$ ratio is depleted by the capture of thermal neutrons,

$$n + ^{149}\text{Sm} \rightarrow ^{150}\text{Sm} + \gamma. \quad \text{(10)}$$

The cross section is dominated by a very low energy resonance, involving an almost exact cancellation between Coulomb and strong effects. Thus, even a small change in $\alpha$ could be significant. This was analyzed by Damour and Dyson\(^{22}\) who found that $\dot{\alpha}/\alpha$ is bounded to be between $-6.7 \times 10^{-17}/\text{yr}$ and $+5.0 \times 10^{-17}/\text{yr}$, and by Fujii et al.\(^{23}\), who obtained $\dot{\alpha}/\alpha = (-0.2 \pm 0.8) \times 10^{-17}/\text{yr}$, both over $2 \times 10^9\text{ yr}$. This is a very stringent result, but does not directly contradict (8) because the latter refers to an earlier time period (around $(6 - 11) \times 10^9\text{ yr}$ ago). Furthermore, only the possible variation in $\alpha$ was considered in\(^{22,23}\). It is conceivable that the effects of

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\(^a\)Laboratory limits are reviewed in detail in\(^5\).
varying $\alpha$ could have been cancelled by a change in the strong interaction strength, $\alpha_s$.

Big Bang Nucleosynthesis, which occurred for redshift $\sim 10^9 - 10^{10}$, implies $^{24}$ that $\frac{\Delta \alpha}{\alpha} < O(10^{-2})$, assuming that only $\alpha$ varies. This is weak compared with (8) if $\dot{\alpha}/\alpha$ is constant in time, but could conceivably be important if there were significantly enhanced effects at large redshift.

CMB results may eventually be able to constrain $\frac{\Delta \alpha}{\alpha}$ at the $10^{-2} - 10^{-3}$ level for $z \sim 1000$ from their effects on the ionization history of the Universe $^{25}$.

4. Correlations with $\alpha_s$, $h$, $v$, $G_N$, ···

If $\alpha$ varies with time, it is likely that other fundamental constants do also. The correlations of their time dependences would be a probe of the underlying theory of particle physics $^{2,4,14,15}$.

For example, the observed low energy gauge couplings are consistent with the unification of the running gauge couplings at a scale $M_G \sim 3 \times 10^{16}$ GeV, predicted in simple supersymmetric grand unification $^{26}$:

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_G} + b_i t_G$$

where $\alpha_i, i = 1, 2, 3$ are the gauge couplings associated with $U(1) \times SU(2) \times SU(3), t_G = \frac{1}{4} \ln \frac{M_Z}{M_G} \approx 5.32, \alpha_G^{-1} \approx 23.3$ is the inverse of the common coupling at the unification scale, and the $b_i$ are the beta function coefficients. In the MSSM, $b_i = (\frac{33}{5}, 1, -3)$. The (running) electromagnetic fine structure constant is related by $\alpha^{-1} = \frac{5}{3} \alpha_1^{-1} + \alpha_2^{-1} \sim 127.9$, where all three couplings are evaluated at $M_Z$. If gauge unification holds, either in the simple MSSM framework or something similar, then it is likely that all three gauge couplings will vary simultaneously $^{2,14}$.

The simplest possibility is that the dominant effect is a time variation in $\alpha_G^{-1}$. In that case, it is straightforward to show $^2$ that the strong coupling $\alpha_s = \alpha_3$ has a magnified variation,

$$\frac{\Delta \alpha_s}{\alpha_s} \simeq 3 \frac{\alpha_s}{8} \frac{\Delta \alpha}{\alpha} \sim 5.8 \frac{\Delta \alpha}{\alpha}$$

where $\alpha_s$ is evaluated at $M_Z$ and we ignore the difference in the relative variation of $\alpha$ between scales 0 and $M_Z$. There is an even stronger variation in the QCD scale $\Lambda_{QCD}$, at which $\alpha_s$ becomes strong,

$$\frac{\Delta \Lambda_{QCD}}{\Lambda_{QCD}} \sim 34 \frac{\Delta \alpha}{\alpha}.$$
which is around \(-25 \times 10^{-5}\) for the Webb et al. value (8). This has a theoretical uncertainty (given the assumptions) of around 20%. Most hadronic mass scales (with the exception of the pion mass) are approximately proportional to \(\Lambda_{\text{QCD}}\), so they are expected to have the same relative variation.

It is also reasonable to consider a variation in the electroweak scale \(v \sim 246 \text{ GeV}\) (which sets the scale for \(M_Z = g_W v\), where \(\alpha_W = g_W^2 / 4\pi = 3\alpha_1 / 5 + \alpha_2\) ), or more precisely in the ratio of \(v\) to the unification scale \(M_G\). (Only dimensionless ratios of mass scales are physically relevant, so we are implicitly measuring all masses with respect to \(M_G\).) In \(^2\) we define the phenomenological parameter \(\kappa\) by

\[
\frac{\Delta v}{v} \equiv \kappa \frac{\Delta \alpha}{\alpha},
\]

which implies that

\[
\frac{\Delta \alpha_S}{\alpha_S} \sim \frac{3}{8} \frac{\alpha_S}{\alpha} \left( 1 - \frac{10}{\pi} \right) \frac{\Delta \alpha}{\alpha}
\]

\[
\frac{\Delta \Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}} \sim 34 \left( 1 + 0.005\kappa \right) \frac{\Delta \alpha}{\alpha}.
\]

These corrections are small for \(\kappa\) of order unity, but important for larger \(\kappa\). In fact, it is shown in \(^2\) that \(\kappa \sim 70\) in theories in which \(v\) is tied to the scale of soft supersymmetry breaking, and in which supersymmetry breaking occurs in a hidden sector at a scale in which a (unified) gauge coupling becomes strong! Even in this case, the correction to the \(\Lambda_{\text{QCD}}\) variation is only a factor of 1.35.

It is useful to introduce phenomenological parameters for the variation of other fundamental “constants”. In particular, the variation of the Yukawa coupling \(h_a\) for fermion \(a\) (so that its Higgs-generated mass is \(m_a = h_a v\)) is parametrized as

\[
\frac{\Delta h_a}{h_a} = \lambda_a \frac{\Delta \alpha}{\alpha}.
\]

Similarly, the variation of the Planck scale \(M_{\text{PL}} = G_N^{-1/2}\) (again, only the ratio of \(M_{\text{PL}}\) to other mass scales is relevant) is parametrized as

\[
\frac{\Delta M_{\text{PL}}}{M_{\text{PL}}} = \beta \frac{\Delta \alpha}{\alpha}.
\]

The possible variation of various observables can be expressed in terms of these parameters, and their values can in principle be computed in any complete fundamental theory, allowing for a more general treatment of time

\(^2\)The effects of the running of \(h_a\) are described in \(^2\).
variation⁸. For example, for the quantities defined before (9) one predicts⁹ the variations ²,

\[
\frac{\Delta X}{X} \sim (-32 + \lambda + 0.8\kappa) \frac{\Delta \alpha}{\alpha} \sim (23 \pm 6) \times 10^{-5}
\]
\[
\frac{\Delta Y}{Y} \sim (34 - \lambda - 0.8\kappa) \frac{\Delta \alpha}{\alpha} \sim (-24 \pm 6) \times 10^{-5},
\]

(18)

where I have assumed a common value \( \lambda \) for all the Yukawa factors \( \lambda_i \), and the numerical values are evaluated using \( \lambda = \kappa = 0 \) and the Webb et al. value (8). These are to be compared with the experimental results in (9). Clearly, within this framework the observational results in (8) and (9) are consistent only if there is a delicate cancellation of effects, with \( \lambda + 0.8\kappa \sim 32 \). Other applications, including big bang nucleosynthesis, the OKLO reactor constraints, and the triple \( \alpha \) process, are considered in ².⁴.¹⁴.¹⁵.

5. Conclusions

- Time (or space) variation of fundamental “constants” is plausible in any theory in which they are dependent on the sizes or properties of extra dimensions, or on other scalar fields.
- The natural scale for such variations in many frameworks is \( \dot{\alpha}/\alpha \sim M_{\text{Pl}} \sim 10^{43}/s \), which is very much larger than what is allowed by observations. However, it is at least possible that the true variations are nonzero but very small for some reason, just as the vacuum energy is much smaller than the natural scale of \( M_{\text{Pl}} \).
- Webb et al.¹ have reported a positive result (8), corresponding to \( \dot{\alpha}/\alpha \sim 10^{-15} \text{yr}^{-1} \sim 10^{-66} M_{\text{Pl}} \) for constant \( \dot{\alpha}/\alpha \).
- If \( \alpha \) varies, then it is possible that other fundamental quantities, such as the other gauge couplings, Yukawa couplings, or the dimensionless ratios of the electroweak, unification, and gravity scales also vary in a correlated way that depends on the underlying physics. Such variations should be allowed for in analyzing experimental/observational results, and can in principle be a significant probe of the underlying physics.

⁸It was argued in ²⁷ that a variation in \( \alpha \) would upset the fine-tuned cancellations of radiative corrections to the cosmological constant with other contributions, with enormous effect. We take the view that such arguments are not conclusive given our lack of understanding of why \( \Lambda_{\text{cosm}} \) is so small.

⁹We ignore possible variations in \( g_P \) because it is well described in the constituent quark model, where it is a Clebsch-Gordan coefficient.
• The comparison between different classes of observations depends on the time dependence of $\dot{\alpha}/\alpha$, which in turn depends on the type of scalar fields involved and their potentials.
• There may be long-ranged forces associated with the time variation $^{13}$.

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