

Were Fundamental Constants Different in the Past?

Atomic physics, nuclear physics, and cosmology enable physicists to probe changes in the fine-structure constant over time scales ranging from a few years to nearly the age of the universe.

Keith A. Olive and Yong-Zhong Qian

Are any of nature's fundamental parameters truly constant? If not, are they fixed by the vacuum state of the universe, or do they vary slowly in time even today? To fully answer those questions requires either an unambiguous experimental detection of a change in a fundamental quantity or a significantly deeper understanding of the underlying physics represented by those parameters.

At first glance, a long list of quantities usually assumed to be constant could potentially vary: Newton's constant G_N , Boltzmann's constant k_B , the charge of the electron e , the electric permittivity ϵ_0 and magnetic permeability μ_0 , the speed of light c , Planck's constant $\hbar$, Fermi's constant G_F , the fine-structure constant $\alpha = e^2/\hbar c$ and other gauge coupling constants, Yukawa coupling constants that fix the masses of quarks and leptons, and so on. One must, however, distinguish what may be called a fundamental dimensionless parameter of the theory from a fundamental unit. Dimensionless parameters include gauge couplings and quantities that, like the ratio of the proton to electron mass, are combinations of dimensioned quantities whose units cancel. Their variations represent fundamental and observable effects.

In contrast, variations in dimensioned quantities are not unambiguously observable. (For an interesting and thought-provoking discussion on the number of fundamental units in physics, see reference 1.) To point out the ambiguity is not to imply that a universe with, say, a variable speed of light is equivalent to one in which the speed of light is fixed. But no observable difference between those two universes can be uniquely ascribed to the variation in c . It thus becomes operationally meaningless to talk about measuring the variation in the speed of light or whether a variation in α is due to a variation in c or $\hbar$. It is simply a variation in α .

Lev Okun provides a nice example, based on the hydrogen atom, that illustrates the inability to detect the variation in c despite the physical changes such a variation would cause.² Lowering the value of c lowers the rest-mass energy of an electron, $E_e = m_e c^2$. When $2E_e$ becomes smaller than the binding energy of the electron to the proton in a hydrogen atom, $E_b = m_e e^4/2\hbar^2$, it becomes energetically favorable for the proton to decay to a hydrogen atom and a positron. Clearly, that's an observable effect providing evidence that some constant of nature has changed. However, the quantity that determines whether the above decay occurs is the ratio $E_b/2E_e = e^4/4\hbar^2 c^2 = \alpha^2/4$.

Therefore, one cannot say which constant among e , $\hbar$, and c is changing, only that the dimensionless α is.

A brief history of time variation

The notion of time-varying constants goes back to the late 1930s, when Paul Dirac proposed his large-number hypothesis. Dirac noticed that the ratio of the electromagnetic to the gravitational interaction between a proton and an electron, $e^2/G_N m_p m_e \sim 10^{40}$, is roughly the same as the ratio of the size of the observable universe to the classical radius of the electron, $m_e c^3/e^2 H_0 \sim 10^{40}$, where $H_0 = 70 \text{ km}/(\text{s} \cdot \text{megaparsec})$ is the present-day Hubble parameter. Furthermore, both ratios are roughly the square root of the total number of baryons in the observable universe, $c^3/m_p G_N H_0 \sim 10^{80}$. Dirac supposed that if the relationships among those ratios is not coincidence, then they should remain constant over time. Noting that the Hubble parameter is not constant (roughly speaking, it is inversely proportional to the age of the universe t), he proposed that $G_N \propto 1/t$. He could, however, have just as easily suggested that $e^4/(m_e)^2 \propto t$, and the relationships among the large numbers would be maintained. Dirac's choice naturally sets e , c , and m_e as constants. However, one may rather choose Planck units, in which G_N , c , and $\hbar$ are fixed, because only the dimensionless ratios are observable.

Of course, the large-number hypothesis has been excluded by experiment. The corollary prediction (with appropriate parameters taken as fixed) that $(1/G_N)dG_N/dt$ is about $-10^{-10}/\text{yr}$ is some two orders of magnitude larger than the limits obtained with the Viking Landers on Mars. The limit from Big Bang nucleosynthesis is comparable.

Extensions of Albert Einstein's theory of general relativity can realize variations in Newton's constant. In the simplest such extension, one adds a scalar field, as described in box 1. The predictions of the extended theory may be described in terms of two so-called post-Einstein parameters β and γ , whose values are exactly 1 in general relativity. A recent experiment³ has determined that $(\gamma - 1) = (2.1 \pm 2.3) \times 10^{-5}$, a constraint that represents an order-of-magnitude improvement over previous results. Modifications of general relativity typically lead to violations of the equivalence principle. Tests of the principle, in turn, can be used to set model-dependent constraints on the variations of fundamental couplings.

Observations^{4,5} of quasar absorption systems (see figure 1) at cosmological redshifts $z = 0.5\text{--}3.0$ have piqued interest in the idea that the fundamental constants of nature vary in time. After comparing several transition lines from several elemental species (we offer technical details and further discussion below) James Webb, Michael Murphy, Victor Flambaum, and colleagues reported the statistically significant result $\Delta\alpha/\alpha = (-5.4 \pm 1.2) \times 10^{-6}$. The

Keith Olive is the director of the William I. Fine Theoretical Physics Institute and a Distinguished McKnight University Professor and **Yong-Zhong Qian** is an associate professor and a McKnight Presidential Fellow; both are in the school of physics and astronomy at the University of Minnesota, Minneapolis.

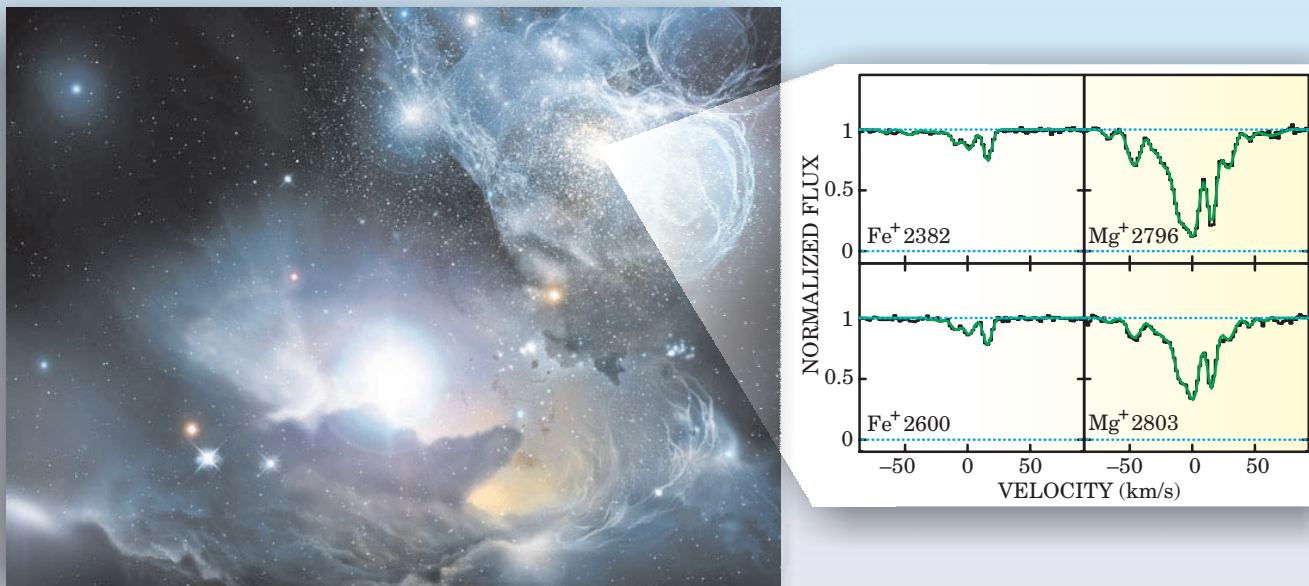


Figure 1. A gaseous cloud lies along the line of sight to a distant quasar in this artist's rendition. The iron and magnesium spectra (green; the cosmological redshift is 1.3) on the right both show subtle variations when different lines are compared. By studying such variations for a variety of elements, scientists can probe for changes in the fine-structure constant over cosmological timescales. Velocities in the spectra are given relative to an arbitrary standard. (Drawing courtesy of Wolfram Freudling et al., Space Telescope–European Coordinating Facility, ESO, ESA, and NASA; spectra adapted from M. T. Murphy et al., <http://arXiv.org/abs/astro-ph/0310318>.)

negative sign means that the past value of α is smaller than the present value. Inspired by that provocative result, we concentrate in this article mainly on possible variations of the fine-structure constant.

Various sensitive experimental checks constrain the variation of coupling constants.⁶ Limits can be derived from cosmology (from both Big Bang nucleosynthesis⁷ and the microwave background⁸), the Oklo natural reactor in Gabon,⁹ long-lived isotopes found in meteoritic samples,^{10,11} and atomic clock measurements.^{12–14}

Cosmological bounds

The theory of Big Bang nucleosynthesis describes the production, in the early universe, of the light isotopes deuterium, helium-3, helium-4, and lithium-7. Its success relies on, among other things, a fine balance between the overall expansion rate of the universe, proportional to $(G_N N)^{1/2}$ where N is the number of relativistic particles, and the weak interaction rates that control the relative number of neutrons to protons at the onset of nucleosynthesis. Changes in the weak rates—which may result from changes in fundamental parameters—or a change in the expansion rate affects the neutron to proton ratio and ultimately the ^4He abundance. Thus, one can use the concordance between theory and the observed light-element abundances to constrain the physics of models that go beyond the standard model.

As described in box 2, a key parameter that determines the ^4He mass fraction Y is the difference Δm_N between the neutron and proton masses. That mass difference can be expressed in terms of the quantum chromodynamics (QCD) scale Λ_{QCD} (of order 100 MeV), the energy at which the strong gauge coupling constant becomes of order unity and the theory may be treated perturbatively, and the Higgs expectation value v (of order 100 GeV), which is characteristic of the weak interactions: $\Delta m_N c^2 = a\alpha\Lambda_{\text{QCD}} + bv$. The numbers a and b are determined with theoretical and experimental input. The term involving a shows that

changes in α directly induce changes in Δm_N .

The theoretical prediction for Y agrees with observation to within a few percent, which allows one to deduce that the relative change in α over the 13-billion-year history of the universe has been no more than about 5%. Assuming a constant rate of change over that time, that result is equivalent to $1/\alpha |d\alpha/dt| \lesssim 4 \times 10^{-12}/\text{yr}$ over the past 13×10^9 years.

In the context of unified or string-inspired theories, in which the strong, weak, and electromagnetic gauge couplings come together at a so-called unification scale, one can derive significantly stronger limits on the variation of α . At energies above the unification scale, those theories are characterized by a single gauge constant. At energies below the unification scale, each of the three gauge constants has its own energy dependence, and so the three are distinguishable. Thus, in unified theories, a change in the fine-structure constant implies a change in other couplings. The dominant effects are found in induced variations of Λ_{QCD} and v . Because those quantities have dimensions, we are implicitly referring to variations with respect to some fixed mass scale such as the Planck mass, $M_P = (\hbar c/G_N)^{1/2}$.

Exactly how changes in the fine-structure constant are related to changes in the QCD and weak-interaction scales depends on theoretical details, but typically one finds $\Delta\Lambda_{\text{QCD}}/\Lambda_{\text{QCD}} \approx 30\Delta\alpha/\alpha$ and $\Delta v/v \approx 100\Delta\alpha/\alpha$. The Higgs mechanism generates masses that are proportional to v for all quarks and leptons and also for the weak gauge bosons W and Z . Variations in Λ_{QCD} and v translate to variations in all low-energy particle masses. In short, if α varies in unified or string-inspired theories, virtually all masses and couplings likely vary as well, typically much more strongly than the variation induced by changes in the Coulomb interaction alone. As a consequence, the nucleosynthesis bound on α , for example, improves by about two orders of magnitude in unified scenarios.

One can also derive cosmological bounds based on

Box 1. A Simple Extended Gravity Theory

The construction of theories with variable “constants” is straightforward. Consider a gravitational Lagrangian that includes ϕR as one of its terms, where ϕ is a scalar field and R is the Einstein curvature scalar. The gravitational constant is determined if the dynamics of the theory fix the expectation value of the scalar field $\langle\phi\rangle$. That is, in units for which $\hbar = c = 1$,

$$G_N = \frac{1}{16\pi\langle\phi\rangle}.$$

So-called Jordan-Brans-Dicke theories are specific realizations in which scalar fields allow for the possibility of a time-varying gravitational constant. Such theories, however, can always be reexpressed in a way that keeps G_N fixed and shunts the time dependence to other mass scales through their dependence on the scalar field. For example, a simple JBD action can be written as

$$S = \int d^4x \sqrt{g} \left[\phi R - \frac{\omega}{\phi} \partial_\mu \phi \partial^\mu \phi + \Lambda + \mathcal{L}_m \right],$$

where ω is a number that characterizes the degree of departure from general relativity (which is recovered in the limit $\omega \rightarrow \infty$), Λ is the cosmological constant, and the matter Lagrangian for electromagnetism and a single massive fermion can be written as

$$\mathcal{L}_m = -\frac{1}{4e^2} F^2 - \bar{\psi} \not{D} \psi - m \bar{\psi} \psi,$$

where $F^{\mu\nu}$ is the electromagnetic field tensor.

When the action is expressed as above, an evolving scalar field ϕ leads to a varying G_N . However, the JBD action can be expressed in terms of the conformally related metric $\bar{g}_{\mu\nu} = \phi g_{\mu\nu}$ as

$$S = \int d^4x \sqrt{\bar{g}} \left[\bar{R} - \left(\omega + \frac{3}{2} \right) \frac{\partial_\mu \phi \partial^\mu \phi}{\phi^2} - \frac{\bar{\psi} \not{D} \psi}{\phi^{3/2}} - \frac{m \bar{\psi} \psi}{\phi^2} - \frac{1}{4e^2} F^2 + \frac{\Lambda}{\phi^2} \right].$$

In this representation, Newton’s constant is constant, but the fermion mass varies as $\langle\phi\rangle^{-1/2}$ (one needs to rescale ψ) and the cosmological constant varies as $1/\langle\phi\rangle^2$. The physics does not depend on how the action is represented, and, in particular, the measurable dimensionless quantity $Gm^2 \propto 1/\langle\phi\rangle$ is independent of representation.

In the theory described here, the fine-structure constant remains constant. But it is easy enough to construct theories in which it, too, varies. For example, a Lagrangian term ϕF^2 that couples a scalar field to the electromagnetic field tensor fixes the fine-structure constant to be

$$\alpha = \frac{1}{16\pi\langle\phi\rangle}.$$

measurements of the microwave background. As the universe expands, its radiation cools to the “decoupling” temperature T_{dec} , at which protons and electrons can combine to form neutral hydrogen atoms. Once those neutral atoms are in place, photons are decoupled from the protons and electrons. At decoupling, when the universe was some 400 000 years old, $\exp(-E_b/T_{\text{dec}})$ was roughly equal to the number ratio of baryons (that is, protons and neutrons) to photons, about 6×10^{-10} . Measurements of the microwave

Box 2. Big Bang Nucleosynthesis of ${}^4\text{He}$

The helium-4 abundance can be estimated simply from the ratio of the neutron to proton number densities, n/p , by assuming that essentially all free neutrons are incorporated into ${}^4\text{He}$. Thus the mass fraction Y of ${}^4\text{He}$ is

$$Y = \frac{2(n/p)}{1 + (n/p)}.$$

When neutrons and protons are in chemical equilibrium, their relative abundance is determined by the usual Boltzmann exponential. Neutrons and protons cease to be in chemical equilibrium after the temperature falls to the so-called freeze-out temperature, $T_f \approx 0.8$ MeV, at which the weak interaction rate for interconverting neutrons and protons falls below the expansion rate of the universe. At that time, the neutron to proton ratio is given by

$$(n/p) = \exp(-\Delta m_N/T_f),$$

where Δm_N is the neutron–proton mass difference. To estimate Y , one must adjust n/p to account for free neutron decays that occur before the onset of nucleosynthesis at a temperature of about 0.1 MeV.

background can determine the decoupling temperature to within a few percent, which in turn determines E_b at decoupling. Because changes in α lead to changes in E_b , the fine-structure constant can have changed by at most a few percent since decoupling.

Reactors and meteorites

Two billion years ago, in the southeast of Gabon, a natural fission reactor operated at what is now the Oklo uranium mine. By studying the observed isotopic abundance distribution at Oklo—for example, the ratio of samarium-149 to samarium-147—one can derive constraints on the variation of α .⁹

The Sm isotopic ratio is of special interest because it can be related to the cross section for the radiative neutron capture of ${}^{149}\text{Sm}$ to yield an excited state of ${}^{150}\text{Sm}$. That cross section, in turn, depends sensitively on the resonance energy E_r for the capture. The observed isotopic ratios at Oklo determine the value E_r had 2 billion years ago, which can be compared to the current value of 0.0973 eV. The change in the resonance energy $|\Delta E_r/E_r| \lesssim 1$ can then be related to a change in α .

One contribution to the resonance energy comes from the Coulomb energy $E_c = (3/5)(e^2/r_0)Z^2/A^{1/3}$, where Z is the number of protons in the nucleus, $A - Z$ the number of neutrons, and $r_0 = 1.2$ femtometers. The Coulomb contribution clearly scales with α . If all the change in the resonance energy can be attributed to a change in the Coulomb term, then $|\Delta E_r| = 1.16|\Delta\alpha/\alpha|$ MeV, from which one can obtain the limit $|\Delta\alpha/\alpha| \lesssim 10^{-7}$. Allowing all fundamental couplings to vary interdependently yields the more stringent limit $|\Delta\alpha/\alpha| < 5 \times 10^{-10}$.

Precise meteoritic data coupled with present laboratory measurements of the decay rates for the long-lived isotopes rhenium-187, uranium-235, and uranium-238 constrain the beta-decay rate of ${}^{187}\text{Re}$ back to the time of solar system formation—about 4.6 billion years ago.¹¹ Armed with those constraints, one can derive limits on possible variations of the fine-structure constant at a redshift of 0.45 or so. That redshift value borders the range of redshifts over which observations of quasar absorption systems suggest variations in α . The pioneering studies on the

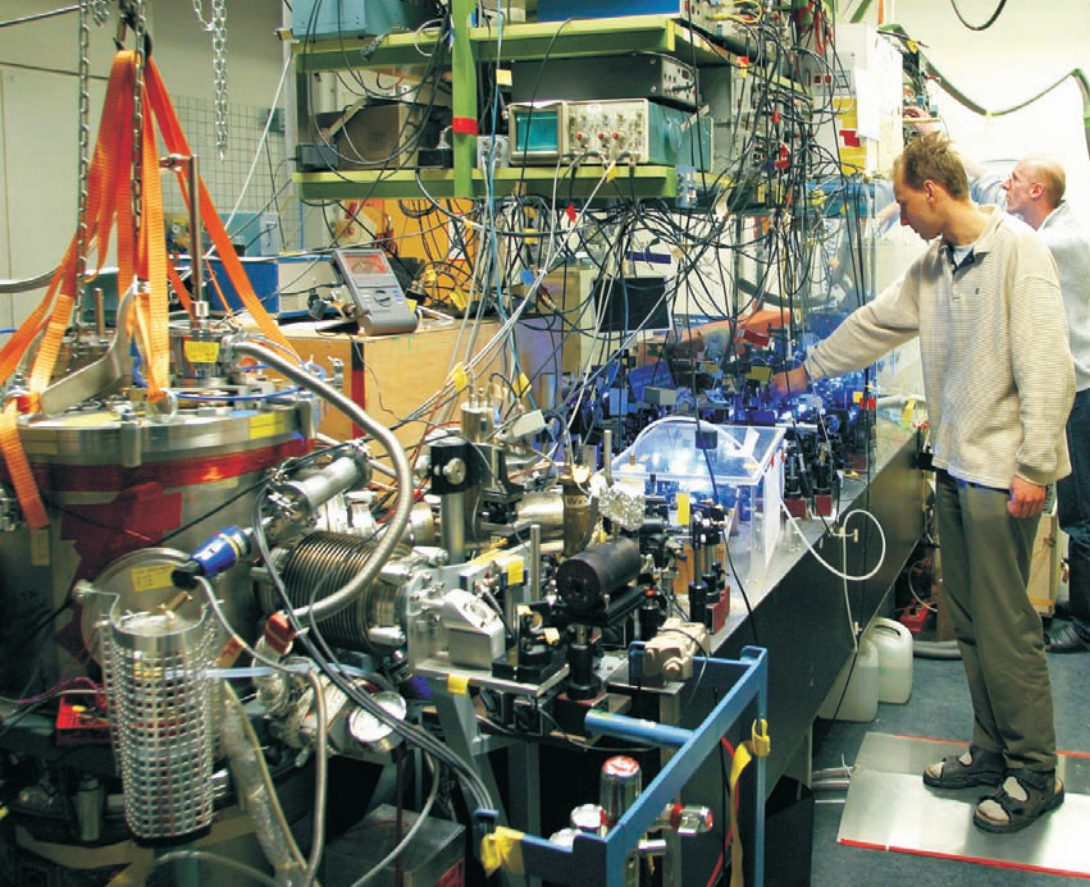


Figure 2. Electronic transitions in hydrogen, when compared with hyperfine transitions in cesium-133, constrain variations in the fine-structure constant. The hydrogen beam apparatus is visible in the front of this experiment, which was conducted at the Max Planck Institute for Quantum Optics in Garching, Germany. Behind the apparatus, Nicolai Kolachevsky (forefront) and Marc Fischer adjust the laser system. (Courtesy of Theodor Hänsch.)

U–Pb age of those meteorites and the slope of the Re–Os line, one can precisely determine λ_{187} .

The derived value of λ_{187} covers decay over the past 4.6 billion years. By comparing it with the present value of the decay rate, as measured in the laboratory, one can limit the variation of α to $\Delta\alpha/\alpha = (8 \pm 8) \times 10^{-7}$. Again, if one allows all fundamental couplings to

vary interdependently, a more stringent limit, $\Delta\alpha/\alpha = (2.7 \pm 2.7) \times 10^{-8}$, may be obtained.

Atomic clocks

Measurements of transition frequencies in atomic clocks have set impressive bounds on the variation of α over the past several years. Those experiments consider two kinds of transition: electronic transitions, in which the spatial wavefunctions of electrons change, and hyperfine transitions during which only the total spin of the electron and nucleus changes.

The electronic transition frequency ν_{el} depends on a relativistic correction F , which is a function of α and the atom undergoing the transition. The hyperfine transition frequency ν_{hf} depends on $(\mu/\mu_B)\alpha^2 F$, where μ is the nuclear magnetic moment of the relevant atom and μ_B is the Bohr magneton. For atoms X and Y ,

$$\nu_{hf}(X)/\nu_{hf}(Y) \propto [\mu(X)/\mu(Y)] F(X,\alpha)/F(Y,\alpha) \text{ and}$$

$$\nu_{hf}(X)/\nu_{el}(Y) \propto [\mu(X)/\mu_B]\alpha^2 F(X,\alpha)/F(Y,\alpha).$$

If one supposes that the Bohr magneton and all magnetic moments are fixed so that only α can vary, then either of the frequency ratios given above can be used to probe for changes in α .

Three experiments conducted over the past several years have led to markedly improved constraints on the recent variation of α . Measurements comparing hyperfine transitions in rubidium-87 and cesium-133 over a four-year period¹² have established the limit $|\Delta\alpha/\alpha| < 5 \times 10^{-15}$. A three-year observation¹³ of the electric quadrupole transition in singly charged mercury-199 and of the ground-state hyperfine transition of ¹³³Cs determined that $|\Delta\alpha/\alpha| < 4 \times 10^{-15}$. A third experiment (see figure 2) compared the hyperfine transition in ¹³³Cs to 1S–2S electronic transitions in atomic hydrogen. Independent electronic-transition measurements taken 3.6 years apart determined

effect of variations of fundamental constants on radioactive decay rates were performed by James Peebles and Robert Dicke and by Freeman Dyson.¹⁰

The β -decay rate λ is proportional to some power n of the energy Q released during the decay. As with the resonant energy for neutron capture, the Coulomb energy E_C contributes to Q . As a consequence, changes in α are related to changes in decay rates.

Isotopes with the lowest Q are typically most sensitive to changes in α because $\Delta\lambda/\lambda = n(\Delta Q/Q)$ is large for small Q . The isotope with the smallest Q (2.66 ± 0.02 keV) is ¹⁸⁷Re, which decays into osmium-187. If some radioactive ¹⁸⁷Re were incorporated into a meteorite formed in the early solar system, the present abundance of ¹⁸⁷Os in the meteorite would be $(^{187}\text{Os})_0 = (^{187}\text{Os})_i + (^{187}\text{Re})_0[\exp(\lambda_{187}t) - 1]$, where the subscripts i and 0 denote the initial and present abundances respectively; λ_{187} is the decay rate for ¹⁸⁷Re; and t is the meteorite's age.

A plot of the present abundance of ¹⁸⁷Os (divided by the present abundance of ¹⁸⁸Os, which does not receive any decay contributions) versus the present abundance of ¹⁸⁷Re (likewise normalized to ¹⁸⁸Os) for samples gathered from iron meteorites gives a straight line. From the slope of that line, one can precisely determine the product $\lambda_{187}t$.

The technique of correlating ¹⁸⁷Re with ¹⁸⁷Os can be applied to other parent–daughter pairs to derive the product of the relevant decay rate and meteoric age. Because the alpha-decay rates of ²³⁸U and ²³⁵U are rather insensitive to variations in fundamental couplings, the decay rates of those isotopes, as determined from laboratory measurements, along with correlations of uranium-isotope abundances to the amount of lead-206 and lead-207 precisely determine the age of angrite meteorites to be 4.558 billion years.

The iron meteorites containing ¹⁸⁷Re were formed within 5 million years of the angrite meteorites. From the

Box 3. Alkali Doublets and Many Multiplets

The line of sight to a distant, high-redshift quasar is often blocked by absorption clouds. The quasar acts as a bright source, and the absorption features seen in its spectra reflect the clouds' chemical abundances.

Consider a doublet absorption feature involving, for example, $S_{1/2} \rightarrow P_{3/2}$ and $S_{1/2} \rightarrow P_{1/2}$ transitions. The overall wavelength position of the doublet is a measure of the redshift of the absorption cloud, but the relative line splitting $\delta\lambda/\lambda$ (with λ the line's wavelength) is a measure of the fine-structure constant. To relate the line splitting to α , recall that the energy splitting due to the spin-orbit coupling is

$$\delta E \propto \frac{e^2}{m^2 r^3} \mathbf{S} \cdot \mathbf{L} \propto m e^8.$$

The relative energy splitting $\delta E/E \propto \delta\lambda/\lambda \propto \alpha^2$. Thus, any change in the relative line spacing between quasar and terrestrial spectra is proportional to $\Delta\alpha/\alpha$.

The more complicated many-multiplet method compares transitions from different multiplets and different atoms and utilizes the effects of relativistic corrections to the spectra.

that $\Delta\alpha/\alpha = (-4.1 \pm 8.2) \times 10^{-15}$ over that period.¹⁴

The data from the two experiments that compared hyperfine and electronic transitions can be combined, which allows one to consider generalized scenarios in which μ/μ_B , in addition to α , may vary. The combined data constrain the recent variations in the fine-structure constant to $(1/\alpha)d\alpha/dt = (0.9 \pm 2.9) \times 10^{-15}/\text{yr}$.

Quasars

Much of the excitement over the possibility of a time-varying fine-structure constant stems from a series of recent observations of quasar absorption systems. In those observations, the so-called many-multiplet method was applied to several transition lines from several elemental species. A key part of the technique, which uses relativistic corrections to the atomic transition spectra frequencies, is to compare spectra whose line shifts are particularly sensitive to changes in α with spectra that don't display such behavior. The comparison allows one to determine $\Delta\alpha/\alpha$ with a sensitivity of order 10^{-6} .

At relatively low redshift ($z < 1.8$), the crucial comparison is between iron and magnesium (representative line spectra for those elements are shown in figure 1). At higher redshifts, an iron-silicon comparison is most important, although in all cases the analysis includes other elemental transitions. Webb and coworkers⁵ applied the many-multiplet method to data, taken by the high-resolution echelle spectrometer (HIRES) on Mauna Kea's Keck I telescope, with redshifts that ranged from about 0.5 to about 3.0. They reported a statistically significant variation in the fine-structure constant $\Delta\alpha/\alpha = (-5.4 \pm 1.2) \times 10^{-6}$.

More recent observations taken with the ultraviolet and visual echelle spectrograph (UVES) at the European Southern Observatory's Very Large Telescope have not duplicated the Webb result. A many-multiplet analysis¹⁵ of several Fe lines from a single source found $\Delta\alpha/\alpha = (0.1 \pm 1.7) \times 10^{-6}$. It is not clear, however, that the single-source Fe result contradicts the Webb result, which relied on a statistical average of more than 100 absorbers and whose data had significant scatter. A more significant disagreement arose from a study¹⁶ that compared Mg and Fe lines in a set of 23 systems. That experiment set a limit on the possible variation of the fine-structure constant

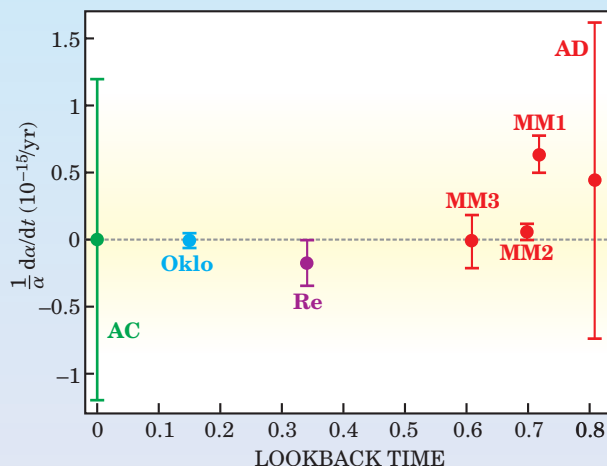


Figure 3. A variety of experiments look for possible changes in the fine-structure constant α over times spanning much of the age of the universe. In this plot, normalized time derivatives, assumed to be constant, are graphed against the lookback time, the fraction of the universe's age that has elapsed between the time of the plotted point and the present. The results summarized come from a representative atomic clock (AC) measurement (from reference 13), isotope distributions in the Oklo natural reactor (Oklo) in Gabon, rhenium-187 decay in meteorites (Re), and many-multiplet (MM) and alkali-doublet (AD) analyses of quasar absorption spectra. Individual quasar results cover a range of times; the plot gives the lookback time corresponding to the mean redshift of an experiment's data. All the results except MM1 (from reference 5) are consistent with zero time variation in the fine-structure constant.

$$\Delta\alpha/\alpha = (-0.6 \pm 0.6) \times 10^{-6}.$$

Although less sensitive than the many-multiplet method, the related alkali-doublet method may also be used to test for variability in α . The relatively simple physics behind the approach is described in box 3. It has been applied to quasar absorption spectra in various experiments¹⁷ and has constrained variations in $\Delta\alpha/\alpha$ with sensitivities ranging from 10^{-4} to 10^{-5} .

The results reported in reference 16 and those based on the statistically dominant subsample of low redshift absorbers described in reference 5 are sensitive to the assumed isotopic abundance ratio of Mg. Both research groups took the Mg abundances to have the same ratios as found in the Sun. That is, they took $^{24}\text{Mg}:^{25}\text{Mg}:^{26}\text{Mg} = 79:10:11$. They further argued, based on then current studies of galactic evolution, that their estimates of the heavy-isotope abundances were, if anything, high: Had they assumed that only ^{24}Mg was present in the quasar absorbers, they noted, they would have obtained significantly different results. The UVES data would have yielded $\Delta\alpha/\alpha = (-3.6 \pm 0.6) \times 10^{-6}$ and the low-redshift subsample of the HIRES data would have given $\Delta\alpha/\alpha = (-9.8 \pm 1.3) \times 10^{-6}$.

The sensitivity to Mg isotopic ratios of results derived from Fe-Mg systems has led one of us (Olive), Grant Matthews, and Timothy Ashenfelter to offer a new interpretation of the many-multiplet analyses.¹⁸ Rather than indicating a variation of α , they may be explained in terms of the early nucleosynthesis of ^{25}Mg and ^{26}Mg . Those heavy isotopes are efficiently produced in intermediate mass stars, particularly those with masses 4–6 times the mass of the Sun, when helium and hydrogen are burning in

shells outside the carbon and oxygen core. According to this new interpretation, the many-multiplet method traces the chemical history of primitive absorption clouds. The hypothesis will be tested by future observations and examinations of correlations among other heavy elements produced in intermediate-mass stars.

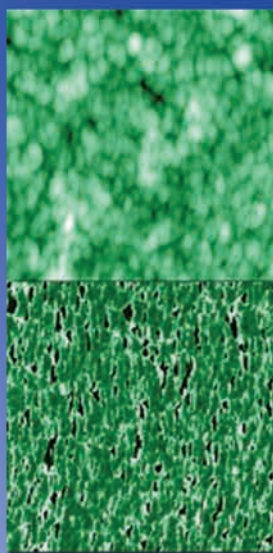
Most physicists take for granted the constancy of fundamental physical constants. However, whether those constants change with time is not just a philosophical question—it can be discussed in plausible theoretical frameworks. Even more important, it has been addressed by a number of observations and experiments. Figure 3 summarizes some of the results discussed in this article. Although most observations and experiments provide constraints on the variation of the fine-structure constant, recent observations of quasar absorption systems have indicated a statistically significant variation. That's an exciting and important result. Does it truly represent a variation of the fine-structure constant or does it have an alternative interpretation in the intricate chemical evolution of the universe? Time will tell.

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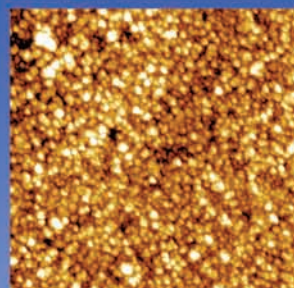
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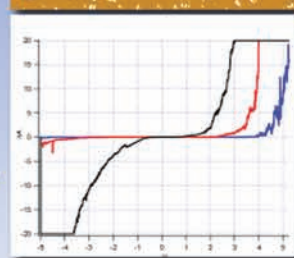
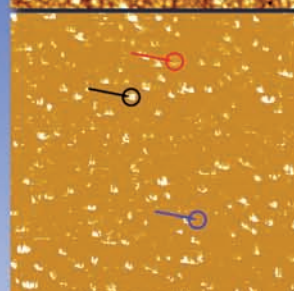


Above: Topography (top) and piezo response of the highly conductive ZnO sample at a bias of 1.5 volts, 2μm scan.

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Right: Topography and current images at a bias of 1.5 volts, 50pA scale, 2μm scan. Measured IV curves are shown from marked areas on the second image. Samples courtesy of Kannan Krishnan Lab, Univ. of Washington.



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