α : a constant that is not a constant?

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Abstract. We review the observational information on the constancy of the fine structure constant α . We find that small improvements on the measurement of ^{187}Re lifetime can provide significant progress in exploring the range of variability suggested by QSO data. We also discuss the effects of a time varying α on stellar structure and evolution. We find that radioactive dating of ancient stars can offer a new observational window.

1 Introduction

The possibility that some of the “fundamental constants” may depend on time was first discussed by Dirac [1]. He remarked that the huge ratio of electric to gravitational forces between a proton and an electron, about 10^{39} , was of the same order of magnitude as the age of the universe in units provided by the atomic constants, $e^2/m_e c^3$. If this coincidence is not casual, then one must have varying constants, their values changing as the age of the universe changes: *“This suggests that the above mentioned large numbers are to be regarded not as constants, but as simple functions of our present epoch, expressed in atomic units In this way we avoid the need of a theory to determine numbers of the order 10^{39} .”* The approach of Dirac to what is now called the hierarchy problem opened a rich field of investigation. The variability of fundamental constants was analysed by Gamow, Dyson and others and then it was forgotten for a while.

Interest in this topic has been revived in the context of string theories, where all the coupling constants and parameters, except the string tension, are actually derived quantities, which are determined by the vacuum expectation values of the dilaton and moduli. Since all these fields evolve on cosmological scales the time variation of the constants of nature during the evolution of the universe arises as a natural possibility, see e.g. [2,3].

On the observational side, Webb et al. [4] have presented evidence for a cosmological evolution of the fine structure constant $\alpha = e^2/\hbar c$. The absorption spectra of diffuse clouds illuminated by quasars suggest that ten billion years ago α was slightly smaller, by about ten part per million. Of course this indication, if confirmed, would have enormous importance.

This short review attempts to provide an answer to some natural questions following the claim of ref.[4]:

- i) What are the observational constraints on the variability of α and how do they compare with the result of ref. [4]?
- ii) What are the prospects for improvements?
- iii) What are the effects of a time varying α on stellar structure and evolution?

Fig. 1. $\Delta\alpha/\alpha$ vs. fractional look-back time to the Big Bang, from [4].

2 What do quasars tell us?

The measurement of the spectra of distant quasars as a mean to study possible variations of α was first suggested by Savedoff [5]. Narrow lines in quasar spectra are produced by absorption of radiation in intervening clouds of gases. Essentially one needs to identify two (sets of) lines, which depend differently on α , so as to extract the value of the redshift factor z together with the value of α at that epoch. The fine structure doublets of “alkali atoms” – a term used to denote atoms and atomic ions with just one electron in the outer shell – are well suited for this study.

This method has been used by several authors and it has been recently applied to a selection of high resolution observations, see [6]. No indication of a variable α has been found and the constraint $\Delta\alpha/\alpha = (-4.6 \pm 4.3[\text{stat}] \pm 1.4[\text{sys}])10^{-5}$ has been obtained [6] on the possible deviation at $z = 2 \div 4$ from the present ($z = 0$) value.

On the other hand, Webb et al. [4] have used a “many multiplet” method, where α is estimated from comparison of the lines of *different* atomic species, so as to obtain a sensitivity gain. The data are summarized in Fig. 1. In this way they claim to have found a deviation from the present α value over the redshift range $z = 1 \div 3$:

$$\Delta\alpha/\alpha = (-0.72 \pm 0.18) \cdot 10^{-5} \quad (1)$$

This result has been criticized in ref. [6] on the grounds that some systematic effect could mimic the variation of α . For example, the lines of the two atomic species considered in [4] are situated in different regions, so that calibration errors could simulate the effect of α variation. In contrast, the method based on the fine splitting of a line of the same species is not affected by these uncertainty sources.

Table 1. Summary on the variation of α

Source	$\Delta\alpha/\alpha$	Look back time (Gyr)	z^*	$\dot{\alpha}/\alpha$ (yr ⁻¹)	ref.
Laboratory	$\leq 1.6 \cdot 10^{-14}$	$4 \cdot 10^{-10}$	0	$\leq 4 \cdot 10^{-14}$	[7]
Oklo	$\leq 1 \cdot 10^{-7}$	1.8	$\simeq 0.1$	$\leq 6 \cdot 10^{-17}$	[11]
Meteorites	$\leq 4 \cdot 10^{-6}$	4.5	$\simeq 0.4$	$\leq 2 \cdot 10^{-15}$	–
¹² C	$\leq 10^{-2}$	$\simeq 10$	$\simeq 1.5$	$\leq 10^{-12}$	–
stellar dating	$\leq 10^{-3}$	$\simeq 10$	$\simeq 1.5$	$\leq 10^{-13}$	–
QSO(doublet)	$\leq 10^{-4}$	$\simeq 11 - 13$	2–4	$\leq 10^{-14}$	[6]
QSO(multiplet)	$+1 \cdot 10^{-5}$	$\simeq 8 - 12$	1–3	$+1 \cdot 10^{-15}$	[4]
CMB	$\leq 5 \cdot 10^{-2}$	$\simeq 14$	$\simeq 10^3$	$\leq 3 \cdot 10^{-12}$	[19]
BBN	$\leq 1 \cdot 10^{-2}$	$\simeq 14$	$\simeq 10^9$	$\leq 7 \cdot 10^{-13}$	[19]

* The red shift – time connection is estimated for $H_o = 68$ Km/s/Mpc, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ ($t_u \simeq 14$ Gyr).

3 Quasars and the rest of the world

The available information on the variability of α is summarized in Table 1. Measurement in the laboratory are sensitive to extremely tiny variations $\Delta\alpha/\alpha \simeq 10^{-14}$, however on a time scale of just a few months. Essentially, one is comparing two clocks (a Hg⁺ atomic clock and a Hydrogen maser), with frequencies which depend differently on α [7]. Experiments with cold atoms will provide a significant sensitivity gain. In fact, the ultimate limit for frequency measurement is observation time. Cold atoms in the laboratory fall due to gravity, whereas atoms in free fall do not fall at all, so let's go to space. This is the idea of an extremely interesting project on the International Space Station, which is expected to explore changes of α to the level $\Delta\alpha/\alpha \simeq 10^{-16}$ [8].

The physics of the fission reactor which nature operated at Oklo about two billion years ago provides a very important constraint. The footprints of natural fission arise from the abundances of rare earth isotopes at the Oklo site, which look similar to those produced by fission *today*. These isotopic abundances are related to large capture cross section of thermal neutrons, which correspond to nuclear resonances at about the thermal energies. The similarity of the abundances means thus that, in two billion years, nuclear energy levels has not varied by more than $kT \simeq 0.1$ eV, a very small range in comparison with the nuclear physics scale. The Coulomb contribution to the difference of nuclear energy levels. $E_{Coul} \simeq \alpha/r_{nuc}$, is thus strongly fixed, corresponding to $|\Delta\alpha/\alpha| \lesssim 10^{-7}$ (barring from accidental cancellation due to variations of other fundamental pa-

rameters). This was first pointed out in [9] and then discussed with much greater detail in [10,11].

The Oklo bound arises, essentially, from the fact that the Q value of a nuclear reaction contains an electromagnetic contribution which is sensitive to changes of α . The constancy of Q , within a small scale of order kT , follows from the observation that reaction rates are the same, now and at the Oklo time. Conceptually, one is again comparing two (nuclear) clocks operating at different times.

A similar argument can be applied to radioactive dating methods. The point is that the lifetimes τ of radioactive nuclei depend on the Q -value of the decay. In addition, α -decay rates have an exponential dependence on α , corresponding to the exponentially small tunnel probability. The most sensitive process is $^{187}\text{Re} \rightarrow ^{187}\text{Os} + e + \bar{\nu}$ due to a very small Q -value: $\Delta\tau/\tau \simeq 1.8 \cdot 10^4 \Delta\alpha/\alpha$ [12], see Table 2. The laboratory measurement $\tau_{1/2}(\text{lab}) = (42.3 \pm 0.7)\text{Gyr}$ (68%C.L.) [15] can thus be compared [17] with the value inferred from Re/Os measurement in ancient meteorites $\tau_{1/2}(\text{met}) = (41.6 \pm 0.42)\text{Gyr}$ [16], dated by means of different radioactive methods (e.g. U/Th method, which is much less weakly affected by variation of α). The agreement within errors (again apart for accidental cancellations) provides a significant constraint, $\overline{\Delta\alpha}/\alpha = (1 \pm 1)10^{-6}$, where the bar denotes an average over the meteorite lifetime. It is not as strong as the Oklo bound, however it explores earlier times. Furthermore, two independent constraints (Oklo and meteorites) are important if one consider the possibility of simultaneous variations of several fundamental parameters.

Cosmic microwave background (CMB) yields information on the variability of α at even earlier times, since decoupling between radiation and matter occurs at the recombination epoch, the time when temperature is so low that atoms can be stable. This clearly depends on the atomic binding energy and thus on α [18]. A change of α also affects the Big-Bang Nucleosynthesis (BBN) mainly through the neutron-proton mass difference, which fixes the neutron density at the weak interactions freeze-out and consequently the primordial ^4He abundance. According to most recent analysis, both CMB and BBN are consistent with a constant α and constrain $\Delta\alpha/\alpha$ to the per cent level, at $z \simeq 10^3$ and 10^9 respectively [19].

For comparing the different information one has to make assumptions about the time evolution of α . The simplest hypothesis is a linear time dependence, which is used in the fifth column of Table 1. In this case the QSO positive result only conflicts with the Oklo bound, which provides the most strict constraint. It is interesting to observe that the meteorites give a bound close to the QSO signal. Improvements in the laboratory measurements of the ^{187}Re lifetime would thus be relevant. The planned atomic physics experiment on the ISS should be capable of exploring the region suggested by QSO.

Let us remark that the QSO-Oklo apparent conflict can be avoided if linearity does not hold. In addition α could depend on place. Also one has to remind that α is not alone; its evolution has to be accompanied by the evolution of other coupling constants, otherwise unification of interactions at the present epoch is just occasional. Actually, unification requires that a change of α is accompanied by a much stronger change in strong interaction parameters, see

e.g. [20]. A change of α corresponds to a change of the QCD scale parameter $\Delta\Lambda_{QCD}/\Lambda_{QCD} \simeq 40\Delta\alpha/\alpha$. This has important consequences, since nucleon and pion masses scale as $M_n \propto \Lambda_{QCD}$ and $M_\pi \propto \sqrt{\Lambda_{QCD}}$. Nuclear radii, which depend on the range of the nuclear force, are thus also sensitive to a change of Λ_{QCD} .

In this situation, the analysis becomes much more complex, see e.g. [20–23] and a complete discussion has not yet been performed. Generally, one can remark the following points:

- Information on the change of α give also information on the couplings of other interactions.

- Several different sources of information are needed, for disentangling the contributions of different effects.

For these reasons, improvements of the various methods, which explore different space-time regions and receive contributions from different interactions, are important so as to confirm or constrain a possible variation of fundamental “constants”.

Table 2. α -dependence of nuclear halfives, from [12]

Nucleus	Decay	$\tau_{1/2}$ [yr]	$d(\ln\tau)/d(\ln\alpha)$
^{238}U	α	$2 \cdot 10^9$	$\simeq -500$
^{40}K	EC	$1.3 \cdot 10^9$	$\simeq +30$
^{187}Re	β	$4 \cdot 10^{10}$	$\simeq +18000$

4 Stars and α

Stars are a useful laboratory for studying fundamental physics. In principle, at least, a change of α over very long times can affect stellar structure and evolution. Clearly, a change of α will affect nuclear fusion rates and opacity. For the former, one has an exponential effect in the tunnelling probability, whereas opacity scales with a small power of α (e.g. $\kappa \propto \alpha^2$ for Thomson scattering). In this spirit we shall briefly discuss a few relevant points:

4.1 The Sun

Helioseismology has provided us with a detailed knowledge of the present solar interior, well in agreement with Standard Solar Model (SSM) calculations which have been performed by assuming that α has been constant. Can a time dependent α spoil this agreement? We have constructed solar models with a linearly time dependent α such that the difference between solar formation and present

is $\Delta\alpha/\alpha = 10^{-2}$. Note that this is a much larger variation than that implied by Oklo and/or meteorite constraints. The tiny difference in sound speed with respect to the SSM is well within the errors of helioseismic determination, see Fig. 2.

Fig. 2. Relative difference (model-SSM)/SSM of (isothermal) sound speed squared as a function of the radial coordinate for a time variation of α such that the difference between sun formation and present is $\Delta\alpha/\alpha = 10^{-2}$. The 1σ (3σ) helioseismic uncertainty corresponds to the dark (light) area, from [24].

4.2 Globular clusters

As well known, the evolution of these systems provides a powerful method for determining the age of the Galaxy, see. e.g. [25]. Is this dating method affected by a time variation of α ? Again the answer is negative, even for variation at the percent level over the Galaxy age, see Fig. 3, where we present isochrones at $t = 11$ Gyr calculated for the M68 cluster, as an illustrative example.

4.3 Stellar nucleosynthesis of ^{12}C

Our very existence relies on a nuclear accident, i.e. a suitably ^{12}C excited level which allows the carbon synthesis by means of $\alpha + \alpha + \alpha \rightarrow ^{12}\text{C}^* \rightarrow ^{12}\text{C} + \gamma$.

Fig. 3. Isochrones calculated with constant α (solid line) and with a time dependent α such that the difference between cluster formation and present is $\Delta\alpha/\alpha = 10^{-2}$ (red dashed line). The two curves look almost undistinguishable.

Carbon synthesis occurs at $kT \simeq 10\text{KeV}$ and the resonance position is measured at $(m_{12}^* - 3m_4)c^2 = 379.5\text{KeV}$. The observation of carbon in ancient stars implies that some 10 Gyr ago the resonance energy was the same, within kT . Thus the Coulomb contribution to the energy difference levels (about α/r_{nuc}) has not changed by more than kT , which implies $\Delta\alpha/\alpha \leq 10^{-2}$. Essentially, this is the same argument as for the Oklo reactor, however the bound is weaker since kT is larger.

4.4 Radioactive dating of ancient stars

In the last few years, radioactive dating has been extended beyond the solar system, see e.g. [13]. Thorium dating of field halo stars and globular cluster stars yields ages on the order of (15 ± 4) Gyr, in agreement with the value derived from globular cluster evolution. Furthermore, recently the age of an old star ($\tau \simeq 12$ Gyr) has been determined by means of *both* Th and U dating [14] so that two clocks are available! The two methods are in agreement within errors of about 3 Gyr, under the assumption that nuclear lifetimes have remained constant. By exploiting the different α dependence of the decay rates, (from [12] one derives $\frac{d(\ln\tau)}{d(\ln\alpha)} = -450$ and -470 for ^{238}U and ^{232}Th respectively) the coherence of

results implies that α has remained constant to the level $\Delta\alpha/\alpha \simeq 2.5 \cdot 10^{-2}$ on a 12 Gyr scale. There is a substantial cancellation of the α varying effect due to the similar α -dependence of the two nuclear clocks. One can achieve a stronger constraint by comparing the Uranium clock with the dating provided by globular cluster evolution (which is not affected by α changes). In this case one has $\Delta\alpha/\alpha \lesssim 10^{-3}$.

The measurement of stellar age from Uranium decay is at presently limited by incomplete knowledge of oscillator strengths and production rates of the elements produced in the r-process. However, significant progress can be expected, as theory and observation shall progress.

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