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Do the fundamental physical constants have the same values in different regions of space–time?

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An analysis of quasar spectra yields highly reliable constraints on the possible variation of the fine-structure constant α and the proton-to-electron mass ratio μ during cosmological evolution from the epoch corresponding to a cosmological red shift $z \approx 2.8$ (i.e., $\sim 10^{10}$ years ago) to the current epoch ($z=0$): $|\dot{\alpha}/\alpha| < 2\times 10^{-14}\ \mathrm{yr}^{-1}$ and $|\dot{\mu}/\mu| < 2\times 10^{-14}\ \mathrm{yr}^{-1}$.

1. INTRODUCTION

Constants characterizing various interactions are known to be related to one another and to depend on interaction energy.[1] However, this dependence is manifested only at very high energies (hundreds of MeV or more). Although the tabulated values of the constants pertain only to comparatively low energies, they cover the overwhelming majority of natural phenomena and experiments. It is these low-energy limits that will be examined in this report.

We note that it is actually only dimensionless combinations of physical constants, which do not depend on the choice of units of measure, that have fundamental significance. We shall consider two such combinations: the fine-structure constant $\alpha = e^2\pi c = 1/137.035\,999\,93\,(52)$ (the numerical value is after Ref. 2; the error in the last significant digits is indicated in parentheses) and the proton-to-electron mass ratio $\mu = m_p/m_e = 1836.152\,701\,(37)$ (i.e., the proton mass in the Hartree system of units; the value from Ref. 3 is given). Here $c = 299\,792\,458 \mathrm{m}\cdot\mathrm{s}^{-1}$ is the speed of light in free space (which is presently taken as a conversion factor for going from units of time to units of length[3]), $e = 4.803\,204\,251(10)\times 10^{-10}$ esu is the charge of an electron, $\hbar = 1.05457162(8)\times 10^{-27}$ erg·s is Planck's constant divided by 2π, $m_p = 1.672\,621\,62(15)\times 10^{-24}$ g is the proton mass, and $m_e = 9.109\,382\,1(8)\times 10^{-28}$ g is the electron mass (all the values were taken from Ref. 4).

The constant α is a basic parameter of quantum electrodynamics, while μ is related to the strong interaction coupling constant. The parameters α and μ are decisive for the spectra of atoms and molecules, respectively.

It can be seen from the numerical values given that most fundamental constants are measured within a relative error of $\sim 10^{-8}$. The reproducibility of these measurements includes the appreciable variation of the parameters during a short time interval, but does not include their variation during the existence of the Universe ($\sim$15 billion years). Moreover, the values of the constants might be different in spatially distant regions of the Universe.

The problem of the possible variation of the fundamental physical constants was first discussed by Milne[5] and Dirac,[6] who advanced their famous large numbers hypothesis. This problem was subsequently examined by many investigators (see, for example, Ref. 7, as well as the references cited in Ref. 8), but it has become especially acute in recent years in connection with the precipitous development of the grand unified theories (GUTs) for the strong and electroweak interactions, as well as some more general theoretical schemes, in which the gravitational interaction is also included.[9,10] It follows from the theories indicated that fundamental constants might have different values in other cosmological epochs, as well as in spatially distant regions of the Universe. That these values are identical in different, even causally unrelated regions of space–time, is not a trivial fact. However, different versions of the theory predict different spatiotemporal dependences of the fundamental constants. Experiments are needed to ascertain which of the theoretical models is correct.

This report presents the results of a study of the spectra of distant extragalactic objects, which permit the establishment of new, the most reliable to date, upper limits on the possible spatiotemporal variation of α and μ.

2. TESTING METHODS

Experimental tests for the possible inconstancy of fundamental constants can be classified according to the spatiotemporal regions of the Universe covered by them. The first group is comprised of laboratory measurements, which cover no more than a few years. The second group includes "local tests," which are concerned with the Earth and the solar system and cover up to 4.5 billion (4.5×10^9) years. Finally, the third group is comprised of astrophysical testing methods, which are based on data from extragalactic astronomy and cover practically the entire period of existence of the Universe.

Laboratory tests are generally confined to comparing frequency standards based on various physical phenomena, which consequently depend differently on the values of different physical constants. If the constants would vary, standards which were initially matched to one another would become unmatched with the passage of time. One of the standards compared is generally the cesium frequency standard, which is presently taken as a basis for defining a unit of time. In particular, different groups of researchers have compared the output frequency of stabilized lasers and masers with it. The accuracy of these experiments permitted the detection of relative changes in the fundamental constants at the level of $\sim 6\times10^{-14}$ per year, but no statistically significant effect was discovered.[11]

''Local tests'' are based on an analysis of changes which would occur in the motion of the Earth and other bodies of the solar system, as well as in the physical conditions and processes on them, if the fundamental constants would vary. Such an analysis is capable of providing a higher accuracy than laboratory measurements, mainly because it permits tracing changes which occur over the course of a far greater time. For example, by analyzing the isotopic composition of meteorites and ancient terrestrial rocks, we can estimate the characteristic alpha- and beta-decay times of the long-lived radioactive elements in them and compare these times to the half-lives measured in the laboratory. The half-lives of such elements are very sensitive to the value of the fine-structure constant α. On the basis of such an analysis Dyson[7] showed that the relative change in α cannot exceed $\sim 10^{-14}$ per year. The limit $|\dot{\alpha}/\alpha| < 2\times10^{-15}$ yr^{-1} was subsequently obtained on the basis of refined data on the beta decay of ^{187}Re (Ref. 12).

A more rigorous estimate was obtained by Shlyakhter.[13] He used data on the isotopic composition of Sm in the ''spent fuel'' of a natural nuclear reactor, which operated 1.8 billion years ago at the site of the contemporary Oklo uranium mine in Gabon. A more detailed analysis was recently performed by Damour and Dyson.[14] They concluded that the rate of relative variation of the fine-structure constant $\dot{\alpha}/\alpha$ is no greater than 10^{-17} per year.

The weak spot in the local tests just described is their dependence on the model of the phenomenon studied. The model is usually fairly complicated and includes a number of physical parameters. In particular, Damour and Dyson assumed in their analysis that the electrostatic (Coulomb) energy of the excited ^{150}Sm nucleus into which a ^{149}Sm nucleus is converted after neutron capture exceeds the electrostatic energy of a ^{150}Sm nucleus in the absence of excitation. However, it is known from experiments that such an hypothesis is far from always correct: the root-mean-square radii of excited nuclei can be greater than or smaller than the radii of the corresponding nuclei in the ground state.[15,16] This constraint becomes even more doubtful if it is taken into account that different physical parameters are interdependent and could have varied synchronously during cosmological evolution. As was shown in Ref. 17, this could have weakened the limit by more than an order of magnitude. In addition, it was noted in Refs. 18 and 9 that if the fundamental constants depend nonlinearly on time, as is assumed in modern theories, constraints which are valid for one time interval do not apply to another. As we have noted above, there might also be a simultaneous spatial dependence. Thus constraints which are valid for the solar system cannot be arbitrarily extended to more distant regions of space and to earlier stages in the life of the universe. Only extragalactic astronomy affords the possibility of investigating these regions of space–time.

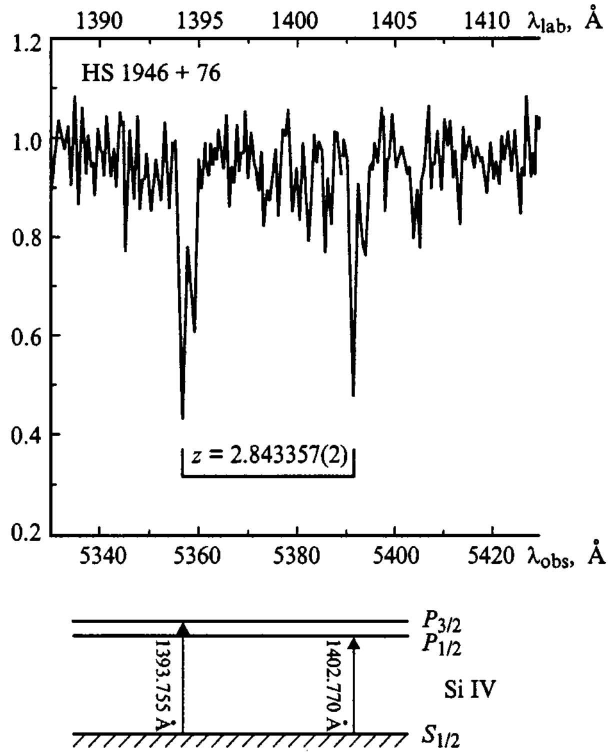

FIG. 1. Finely split doublet of the Si IV resonance line in the spectrum of the quasar HS 1946+76 recorded on the 6-meter telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences. Scheme of energy levels and transitions corresponding to the lines indicated.

For this purpose it would be useful to analyze the spectra of quasars, which are very powerful sources of radiation and can be seen for distances up to 10–15 billion light years. Along the way, the light coming from them has passed through clouds of interstellar gas in early galaxies and has been partially absorbed by them. Therefore, the spectral lines ''imprinted'' in quasar spectra contain information on the physical conditions and the state of matter in the early stages of the evolution of the Universe in various spatially distant regions of it.

The expansion of the Universe has resulted in increases in the wavelengths of the lines observed in quasar spectra (λ_{obs}) in comparison to their laboratory values (λ_0) according to the proportionality

$$\lambda_{obs} = \lambda_0(1+z),$$

where z is the cosmological red shift.

The value of z can be used to determine t, i.e., the ''age'' of the Universe in the epoch when the spectral line was formed. For example, Figs. 1 and 2 present fragments of the spectra of two quasars and exhibit absorption lines with $z \approx 2.8$. These absorption lines were formed when the Universe was 7–8 times younger than now. To obtain rigorous estimates of the variations of the fundamental constants, the lines studied must be sufficiently narrow and they must be recorded with a high spectral resolution and with a high

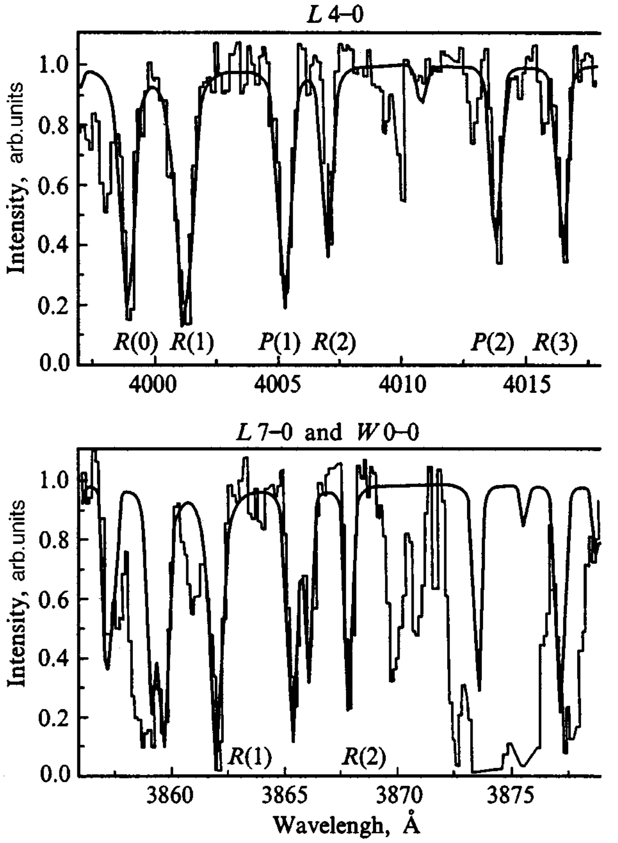

FIG. 2. Fragments of the spectrum of the quasar PKS 0528−250 containing absorption lines of H_2 in the Lyman and Werner series.

signal-to-noise ratio. The lines of the Si IV doublet shown in Fig. 1 and many of the lines of molecular hydrogen in Fig. 2 satisfy this condition.

3. DOES THE FINE-STRUCTURE CONSTANT VARY?

In order to ascertain whether the value of α has varied during cosmological time, it would be useful to investigate the fine splitting of the doublet lines of the Si IV, C IV, Mg II, and other ions, which are often observed in the spectra of distant quasars. An example of such spectral lines is shown in Fig. 1. The relative magnitude of the splitting $\delta\lambda/\lambda$ of these lines is proportional to α^2 (to within negligibly small corrections). Therefore, if the value of α varied with time, the relative splitting $\delta\lambda/\lambda$ should depend on the magnitude of the red shift.

In the first stage of our work we re-analyzed all the published data on finely split doublet lines observed in quasar spectra and complied a special catalog of wavelengths of these lines.[19] Altogether we examined about 1500 pairs of doublet lines with red shifts from 0.2 to 3.7. The analysis of these data demonstrated the absence of a statistically significant deviation of $\delta\lambda/\lambda$ from the current value. The rich observational material assembled in our catalog also allowed us to analyze the possibility of differences in the values of α in regions of the Universe that are causally unrelated to one another.[20] It was found that the dependence of the magnitude of the fine doublet splitting (and thus α) on the direction in the celestial sphere falls within the error $|\Delta\alpha/\alpha|<3\times10^{-3}$.

It should, however, be noted that in the overwhelming majority of cases the goal of the observers was not to perform exact measurements of the fine splitting; therefore, a large part of the data treated did not have a very high accuracy. The analysis performed allowed us to optimize the strategy for investigating the dependence of α on z. In the second stage of the work, our program of spectral observations of several quasars, which was aimed at achieving the highest possibility accuracy in measurements of fine splitting with large red shifts, was carried out on the 6-meter telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences.[21] As a result of the implementation of this program, as well as the use of observational data from other telescopes,[22–24] we determined the mean value of the possible deviation of the fine-structure constant for $z=2-4$ from its value for $z=0$ and the measurement errors (both the statistical and systematic errors)[25]

$$\Delta\alpha/\alpha=(-4.2\pm5.4[\mathrm{stat}]\pm8.0[\mathrm{syst}])\times10^{-5}. \tag{1}$$

A comparison of the data obtained on telescopes located in the northern and southern hemispheres allows us to tighten the constraint on the possible dependence of the fine-structure constant on the direction in the celestial sphere to $|\Delta\alpha/\alpha|<2\times10^{-4}$.

A result which has a formally higher accuracy was recently obtained on the basis of observations on the Keck I 10-meter telescope: $\Delta\alpha/\alpha=(-1.88\pm0.53[\mathrm{stat}])\times10^{-5}$ for $z=0.6-1.6$. However, Webb *et al.*[26] did not take into account the systematic error, which results mainly from the uncertainty in the values of the reference (laboratory) wavelengths, and, as can be seen from (1), this error is dominant.

The upper limit corresponding to (1) (at the 2σ significance level) on the mean rate of variation of α during ~10 billion years is

$$|\dot{\alpha}/\alpha|<2\times10^{-14}\ \mathrm{yr}^{-1}. \tag{2}$$

This constraint is five times tighter than the one which we previously obtained,[19,8] and its accuracy is 3.5 times better than that of the precision laboratory measurements in Ref. 11.

4. DOES THE PROTON-TO-ELECTRON MASS RATIO VARY?

The dimensionless constant $\mu=m_p/m_e$ is approximately equal to the ratio between the nuclear strong interaction coupling constant $(g^2/\hbar c)\sim14$ and the electromagnetic coupling constant $\alpha\approx1/137$. Here g is the effective coupling constant, which is calculated from the scattering amplitude of π mesons on nucleons.

The absorption lines of molecular hydrogen H_2 in quasar spectra can be used to ascertain whether the value of μ has varied during cosmological time. The variation of μ can be detected by comparing the wavelengths of various lines in a quasar spectrum and in the laboratory. The key to this technique is that the wavelengths of different lines depend differently on the parameter under study. This makes it possible to separate the cosmological red shift from the shift caused by the variation of μ.

The most suitable system of molecular lines with a large red shift for such an analysis is the system of absorption lines of the H_2 molecule with $z=2.8108$, which was observed by Levshakov and Varshalovich[27] in the spectrum of the quasar PKS 0528–250. We calculated the sensitivity coefficients of the wavelengths of H_2 toward the possible variation of μ (Ref. 28) and analyzed the observational data,[29] using the high-quality spectrum of PKS 0528–250 recorded by Lanzetta *et al.* on the CTIO 4-meter telescope. A fragment of this spectrum is shown in Fig. 2. The results of measurements of the wavelengths of 50 lines of molecular hydrogen with consideration of the sensitivity coefficients just mentioned led to the following estimate of the deviation ($\Delta\mu$) of μ in the epoch corresponding to $z=2.8108$ from its current value:

$$\Delta\mu/\mu=(-11.5\pm 7.6)\times 10^{-5}. \tag{3}$$

In addition, a multivariant statistical analysis of the measured spectrum, including a combined fit of a large number of H_2 lines with respect to their width and intensity, was performed. This analysis yielded

$$\Delta\mu/\mu=(8.3^{+6.6}_{-5.0})\times 10^{-5}. \tag{4}$$

Both estimates are consistent within 2σ with the zeroth hypothesis that there is no variation of μ. Each of them corresponds to a constraint on the mean (during 10 billion years) rate of relative variation of the proton-to-electron mass ratio at the level

$$|\dot{\mu}/\mu|<2\times 10^{-14}\ \text{yr}^{-1}. \tag{5}$$

5. CONCLUSION

An analysis of quasar spectra has enabled us to establish tight upper constraints on the possible variation of α, i.e., the electromagnetic coupling constant, as well as the proton-to-electron mass ratio $\mu=m_p/m_e$. These quantities could have varied if the coupling constants of the strong and electroweak interactions had undergone changes. However, it was found that these constants did not vary within the statistical error during the 10^{10} years which have passed since the formation of the spectra of distant quasars. The upper limits found constrain the mean rate of possible variation of these parameters at the 0.02% level during a period of the order of 10 billion years, which covers 80–90% of the time of existence of the Universe. In addition, the values of the fundamental constant α were found to be identical (within a statistical error of 0.02%) in regions of the Universe which were not causally related in the period when the spectra were formed. This finding can be regarded as an argument which supports the so-called inflationary cosmological model, which presumes a general superfast inflation of the Universe according to an exponential law in a very early stage of cosmological evolution (see, for example, Ref. 30).

As a final note, we stress once again that the constraints which we obtained on the basis of an analysis of quasar spectra cover much more extensive regions of space and time intervals (corresponding to cosmological red shifts up to $z\approx 3.7$) than do local tests (for example, the Oklo phenomenon, which is assigned only to the epoch with $z=0.09$ and to one point in space). In addition, they are far less dependent on model assumptions. They can therefore be recommended as the most reliable limits to date. They can serve as effective criteria for selecting permissible theoretical models of elementary interactions which predict changes in physical constants on the cosmological time scale.

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[1] L. B. Okun, ‘‘Fundamental constants of nature,’’ Preprint ITEP-TH–56/96, Moscow (1996), 10 pp.; http://xxx.lanl.gov/abs/hep-ph/9612249.

[2] T. Kinoshita, IEEE Trans Instrum. Meas. **IM-46**, 108 (1997).

[3] B. N. Taylor and E. R. Cohen, J. Res. Natl. Inst. Stand. Technol. **95**, 497 (1995).

[4] E. R. Williams, R. L. Steiner, D. B. Newell, and P. T. Olsen, Phys. Rev. Lett. **81**, 2404 (1998).

[5] E. A. Milne, **139**, 409 (1937).

[6] P. A. M. Dirac, **139**, 323 (1937).

[7] F. J. Dyson, in *Aspects of Quantum Theory*, edited by A. Salam and E. P. Wigner, Cambridge University Press (1972), pp. 213–236.

[8] D. A. Varshalovich and A. Y. Potekhin, Space Sci. Rev. **74**, 259 (1995).

[9] T. Damour and A. M. Polyakov, Nucl. Phys. B **423**, 532 (1994).

[10] J. D. Barrow, *Theories of Everything. The Quest for Ultimate Explanation*, Clarendon Press, Oxford (1991).

[11] J. D. Prestage, R. L. Tjoelker, and L. Maleki, Phys. Rev. Lett. **74**, 3511 (1995).

[12] M. Lindner, D. A. Leich, R. J. Borg *et al.*, Nature **320**, 246 (1986).

[13] A. I. Shlyakhter, Nature **264**, 340 (1976).

[14] T. Damour and F. Dyson, Nucl. Phys. B **480**, 37 (1996).

[15] R. Engfer, H. Schneuwly, J. L. Vuilleumier *et al.*, At. Data Nucl. Data Tables **14**, 509 (1974).

[16] G. M. Kalvius and G. K. Shenoy, At. Data Nucl. Data Tables **14**, 639 (1974).

[17] P. Sisterna and H. Vucetich, Phys. Rev. D **41**, 1034 (1990).

[18] W. J. Marciano, Phys. Rev. Lett. **52**, 489 (1984).

[19] A. Y. Potekhin and D. A. Varshalovich, Astron. Astrophys., Suppl. Ser. **104**, 89 (1994).

[20] D. A. Varshalovich and A. Yu. Potekhin, Pis'ma Astron. Zh. **20**, 883 (1994) [Astron. Lett. **20**, 771 (1994)].

[21] D. A. Varshalovich, V. E. Panchuk, and A. V. Ivanchik, Pis'ma Astron. Zh. **22**, 8 (1996) [Astron. Lett. **22**, 6 (1996)].

[22] P. Petitjean, M. Rauch, and R. F. Carswell, Astron. Astrophys. **291**, 29 (1994).

[23] L. Cowie and A. Songaila, Astrophys. J. **453**, 596 (1996).

[24] P. J. Outram, B. J. Boyle, R. F. Carswell *et al.*, Mon. Not. R. Astron. Soc. (1998) (in press).

[25] A. V. Ivanchik, Candidate's Dissertation [in Russian], St. Petersburg (1998), 71 pp.

[26] J. K. Webb, V. V. Frambaum, C. W. Churchill *et al.*, Phys. Rev. Lett. **82**, 884 (1999).

[27] S. A. Levshakov and D. A. Varshalovich, Mon. Not. R. Astron. Soc. **212**, 517 (1985).

[28] D. A. Varshalovich and A. Yu. Potekhin, Pis'ma Astron. Zh. **22**, 3 (1996) [Astron. Lett. **22**, 1 (1996)].

[29] A. Y. Potekhin, A. V. Ivanchik, D. A. Varshalovich *et al.*, Astrophys. J. **505**, 523 (1998).

[30] A. Linde, Phys. Scr. T**36**, 30 (1991).

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