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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on March 31, 1993 in the P. L. Kapitsa Institute of Physics Problems. The following reports were presented at the session:

1. *D. A. Varshalovich, S. A. Levshakov, and A. Yu. Potekhin*. Check of the constancy of the fundamental constants over cosmological time.
2. *M. I. Pudovkin and O. M. Raspopov*. Physical mechanism of the action of solar activity and other geophysical factors on the state of the lower atmosphere, meteorological parameters, and climate.

A brief summary of the reports is given below.

D. A. Varshalovich, S. A. Levshakov, and A. Yu. Potekhin. *Check of the constancy of the fundamental constants over cosmological time.* Quasars are the most powerful energy sources in the Universe. Their luminosity can reach 10^{42} W. For this reason they are visible at greater distances than any other objects—up to 10–15 billion light years. But this means that their spectra were formed long before the solar system—estimated to be 4.5 billion years old—was formed. For this reason, unique information about the early evolution of the Universe and the composition of the matter and the physical conditions existing at that distant epoch can be obtained by studying the spectra of distant quasars. In particular, investigation of these spectra makes it possible to check whether or not the values of the fundamental physical constants changed over cosmological time.

The problem of the possible inconstancy of the fundamental "constants" was formulated theoretically by Dirac in 1937.[1] The problem was later studied by Teller,[2] Landau,[3] Brans and Dicke,[4] De Witt,[5] Gamow,[6] and Dyson.[7] Although Dirac's hypothesis was not confirmed in its initial form,[7] interest in this problem intensified again in the 1980s, when it became clear that grand unification theories, such as the Kaluza-Klein model[8–11] or the superstring model,[12] lead to cosmological variation of the interaction parameters. A modern exposition of this question can be found in the paper by Okun'.[13] Thus the constancy of the fundamental constants is itself a nontrivial fact and must be checked experimentally.

It should be noted that the values of the interaction constants are now known with a relative error of the order of 10^{-8}. This eliminates significant variation of the constants over a short period of time, but it does not exclude variation of the constants over cosmological time. The upper limits of such variation are an important criterion for admissable theoretical models of elementary interactions.

Several laboratory investigations, based on a comparison of frequency standards employing different physical phenomena, have been performed in order to clarify the possible time dependence of the physical constants. First, a comparison of the radio frequencies of the hydrogen maser and a cesium standard gave for the ratio of the gyromagnetic ratios of cesium and hydrogen $R_1=g(\mathrm{Cs})/g(\mathrm{H})$ an upper limit for the relative rate of change $|\dot{R}_1/R_1|<10^{-13}$ yr^{-1}.[14] Second, a comparison of the frequencies of high-Q superconducting cavities and a cesium standard gave the limit $|\dot{R}_2/R_2|<4.1\cdot10^{-12}$ yr^{-1} for the combination $R_2=\alpha^3g(\mathrm{Cs})m_e/m_p$, where α is the fine-structure constant and m_e and m_p are, respectively, the electron and proton mass.

A few years ago it was reported that the ratio of the frequencies of quantum optical and radio standards changes.[15] The authors tentatively attributed their result to the secular variation of the combination $R_3=\alpha^2g(\mathrm{Cs})m_e/m_p)^{1/2}$. According to their estimates $\dot{R}_3/R_3=(1.1\pm0.2)\cdot10^{-11}$ yr^{-13}, which corresponds to Dirac's hypothesis. This result aroused debate.[16] It will be shown below that this interpretation does not agree with astrophysical observations.

A number of authors have derived limits on the rate of change of different combinations of the fundamental constants from geophysical, geochemical, and paleontological data also, though most of these limits are indirect and model-dependent (for example, the Oklo phenomenon[17]). Sisterna and Vucetich[18] derived, on the basis of an analysis of a large number of such works, the general limits on the possible rates of change of the physical constants during the epoch of the existence of the solar system. However, these results cannot be extrapolated to earlier stages of the development of the Universe, since different laws of variation of the fundamental constants are theoretically possible.

This problem can be solved by astrophysical methods. Although astrophysical measurements are not as accurate as precision laboratory measurements, the long time interval $\sim10^{10}$ yr makes it possible to obtain stricter estimates for the possible rate of change of the fundamental constants.

The cosmological redshift increases the wavelengths of lines in the spectra of quasars: $\lambda_{\mathrm{obs}}=\lambda_{\mathrm{lab}}(1+z)$. Systems of red-shifted lines are observed right up $z=4.92$. But the wavelength ratio of different lines should then remain unchanged, if the energy of the corresponding levels of atoms, molecules, and ions during the epoch of formation of the spectrum were the same as at present. For this reason, by comparing the values of the redshifts z of different lines in a spectral system it is possible either to observe a change in

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the physical constants or to establish the upper limit of the possible change in the physical constants. This method was first proposed and employed by Savedoff.[19]

The redshifts of optical and radio lines in quasar absorption systems were compared in Refs. 20–23. The upper limit $|\dot{R}_4/R_4| \lesssim 10^{-13}$ yr^{-1} was obtained for the change in the quantity $R_4=\alpha^2 g(\mathrm{H}) m_e/m_p$. However, this estimate is unreliable because of possible systematic errors associated with the fact that the regions emitting in the optical and radio ranges are separated in space.

The method based on measurement of the fine-structure splitting of multiplets does not have this shortcoming. The relative magnitude of this splitting is proportional to $R_5=\alpha^2$. By comparing these quantities for different redshifts it is possible to investigate the variation of the fine-structure constant α with time.

This method is most promising for the absorption lines of lithium—and sodium-like ions corresponding to the transitions $^2S_{1/2} \rightarrow {}^2P_{3/2}$ and $^2S_{1/2} \rightarrow {}^2P_{1/2}$, which are often observed in quasar spectra. First of all, the transitions occur from the same level. Second, the absorption lines are usually narrow, so that their wavelengths can be determined more accurately than that of the emission lines, which are ten times wider.

Estimates giving the limit $|\dot{\alpha}/\alpha| \lesssim 4 \cdot 10^{-12}$ yr^{-1} were obtained in Refs. 20, 24, and 25 from measurements of the fine-structure splitting of lines in the quasar spectra. The number of observations employed in these works was small. Significantly more accurate and reliable estimates could be obtained with the help of a statistical analysis of the observations of different absorption systems. This became possible in the last few years, when a large number of high-quality spectral studies of quasars were performed.

Such an analysis was first made in Ref. 26. The ratio $\Delta\alpha/\alpha$ with $z\sim 2$ was estimated on the basis of 500 pairs of doublet lines of LiI-, NaI-, and KI-like ions, obtained with a resolution of better than 2 Å. Here $\Delta\alpha \equiv \alpha_z - \alpha_0$ is the difference of the fine-structure constants in an epoch corresponding to the cosmological redshift z and in the modern epoch, respectively. It was reported that $\Delta\alpha/\alpha = (2\pm 1)\cdot 10^{-4}$. However, because the errors were not calculated correctly, the estimated standard deviation was approximately six times smaller than the true deviation. In addition, this investigation did not include analysis of selective effects, which could have significantly distorted the distribution of the ratio α_z/α_0. In order to minimize such effects, 36 of the most reliable doublets (narrow, isolated, and quite strong) were selected; this gave the estimate $\Delta\alpha/\alpha = (3\pm 1)\cdot 10^{-3}$ for $z \approx 2$.[27] The fact that these estimates are clearly inconsistent indicates that the initial sample was inhomogeneous. For homogeneous data, as shown in Ref. 28, the distribution of the values of α_z/α_0 will be approximately Gaussian, and their sample average is, as a rule, shifted due to the nonlinear wavelength dependence of the ratio α_z/α_0. The magnitude of the shift depends on the quality of the spectral data and ranges from -0.01% to -1.5%, if the quantity $\sigma_\lambda/(\Delta\lambda)_z$ (where $(\Delta\lambda)_z = (\Delta\lambda)_0(1+z)$ is the observed value of the fine-structure splitting and σ_λ is the standard deviation of the true position of the spectral line) ranges from 5 to 25%, respectively.

A large volume of inhomogeneous data (with a non-gaussian error distribution)—more than 1000 pairs of lines of the ions CIV, NV, OVI, MgII, AlIII, and SiIV with redshifts $z=0.2$–3.7—was analyzed in Refs. 29 and 30. Most of these data are not of as high quality as the sample from Ref. 27, but because the amount of data was large it was possible to obtain narrower limits on the possible variation of α. Inhomogeneous data are best analyzed by robust methods.[31] In Refs. 29 and 30 robust linear regression analysis by the trimmed-average method was used.[32] It was shown that such an analysis makes it possible to narrow by approximately a factor of two the estimated confidence intervals as well as to reduce by an order of magnitude the systematic shift associated with the nonlinearity of the λ-dependence of α_z/α_0. Data on each of the six ions were analyzed separately. In order to check the effect of the quality of the data subsamples of lines with different spectral resolution was analyzed. The applicability of the linear regression model was checked on the basis of a separate analysis of the data from different redshift intervals.

The analysis showed that there is no statistically significant change in α. The estimate $\alpha^{-1} d\alpha/dz = (-0.6\pm 2.8)\cdot 10^{-4}$ was obtained. Converted to the modern epoch, this gives $|\dot{\alpha}/\alpha| < 4\cdot 10^{-14}$ yr^{-1} (at the 95% significance level). Although this limit is weaker than the limit $|\dot{\alpha}/\alpha| < 1.4\cdot 10^{-15}$ yr^{-1}, presented in Ref. 18, it is of independent significance, since it refers to an earlier cosmological epoch (right up to $z\sim 3$) and to more distant regions of the Universe, which were not causally connected to the epoch during which the observed spectra were formed.

Estimates of the possible change in the electron-to-proton mass ratio $R_6 = m_e/m_p$ over cosmological time, which are obtained on the basis of analysis of the electronic-vibrational-rotational absorption spectra of the H_2 molecule, are of independent interest. Thompson was the first to point out the possibility of making such measurements on the basis of the spectra of extragalactic objects.[33] One system (N_2) of absorption lines in the Lyman and Werner absorption bands, which was observed with $z=2.811$ in the spectrum of the quasar PKS 0528-250, has now been established.[34,35] A preliminary estimate[35] gave the limit $|\Delta R_6/R_6| < 2\cdot 10^{-4}$. But the more detailed analysis of these data performed in Ref. 36 gave $|\Delta R_6/R_6| < 2\cdot 10^{-3}$, which corresponds to $|\dot{R}_6/R_6| \lesssim 10^{-3}$ yr^{-1}.

Thus we have obtained the first estimates, for the cosmological epoch corresponding to redshift $z \approx 3$ (10–15 billion years ago), of the upper limits of the relative change in the fine-structure constant, $|\Delta\alpha/\alpha| < 0.2\%$, and the electron-to-proton mass ratio, $|\Delta(m_e/m_p)/\ (m_e/m_p)| < 0.2\%$ (at the 95% statistical significance level).

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