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TESTING COSMOLOGICAL VARIATIONS OF FUNDAMENTAL PHYSICAL CONSTANTS BY ANALYSIS OF QUASAR SPECTRA

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Contemporary multidimensional cosmological theories predict different variations of fundamental physical constants in course of the cosmological evolution. On the basis of the QSO spectra analysis, we show that the fine-structure constant $\alpha = e^2/\hbar c$ and the proton-to-electron mass ratio $\mu = m_p/m_e$ reveal no statistically significant variation over the last 90% of the lifetime of the Universe. At the 2σ significance level, the following upper bounds are obtained for the epoch corresponding to the cosmological redshifts $z \sim 3$ (i.e., $\sim$ 10 Gyr ago): $|\Delta\alpha/\alpha| < 1.6 \times 10^{-4}$ and $|\Delta\mu/\mu| < 2.2 \times 10^{-4}$. The corresponding upper limits to the time-average rates of the constant variations are

$$|\dot{\alpha}/\alpha| < 1.6 \times 10^{-14}\ \mathrm{yr}^{-1} \qquad \text{and} \qquad |\dot{\mu}/\mu| < 2.2 \times 10^{-14}\ \mathrm{yr}^{-1}.$$

These limits serve as criteria for selection of those theoretical models which predict α and μ variation with the cosmological time. In addition, we test a possible anisotropy of the high-redshift fine splitting over the celestial sphere, which might reveal a non-equality of α values in causally disconnected areas of the Universe.

1 Introduction

Contemporary theories (SUSY GUT, superstring and others) not only predict the dependence of fundamental physical constants on energy, but also have cosmological solutions in which low-energy values of these constants vary with the cosmological time. The predicted variation at the present epoch is small but non-zero, and it depends on theoretical model (see, e.g., Ref. [1] for references). In particular, Damour and Polyakov [2] have developed a modern version of the string theory, whose parameters could be determined from cosmological variations of the coupling constants and hadron-to-electron mass ratios. Therefore observational tests of variability of fundamental constants may serve as an important tool for selection of the theoretical models.

Quasar spectra are an important source of our knowledge of physical conditions at early cosmological epochs, related to the redshifts up to $z \sim 4$. In particular, values of physical constants can be extracted from quasar spectroscopic data and compared with the laboratory values at the present epoch. This extragalactic information significantly supplements results obtained within the Solar system, which cover much smaller range of the redshifts, $z < 0.2$. Although astrophysical measurements are generally less accurate than laboratory ones, the large cosmological time scales allow to obtain more stringent estimates of the variation rates of physical constants.

2 Proton-to-Electron Mass Ratio

Electronic, vibrational, and rotational energies of the H_2 molecule each display a different dependence on the reduced mass $m_p/2$. Therefore comparison of the wavelengths of various electronic-vibrational-rotational molecular lines observed in the spectrum of a high-redshift quasar with the corresponding molecular lines observed in laboratory may reveal or limit variation of $\mu = m_p/m_e$. One may obtain a quantitative limit on such variation, provided that the sensitivity coefficients K_i of wavelengths λ_i with respect to the μ variation are known for each of these lines[1]. If the value of μ at the early epoch z of the QSO absorption spectrum formation were different from the contemporary one, then the wavelength ratios would deviate from unity

$$\frac{(\lambda_i/\lambda_k)_z}{(\lambda_i/\lambda_k)_0} \simeq 1 + (K_i - K_k)\left(\frac{\Delta\mu}{\mu}\right) \qquad (1)$$

The object suitable for the analysis is the H_2 absorption system toward PKS 0528-250 at the redshift $z = 2.811$. Recently, Cowie and Songaila[3] observed this quasar with Keck Telescope and arrived at the 95% confidence interval $-5.5\times10^{-4} < \Delta\mu/\mu < 7\times10^{-4}$, based on an analysis of 18 radiative transitions for H_2 molecule.

We have performed a χ^2 profile fitting analysis of a high-resolution spectrum of PKS 0528-250, obtained with the Cerro-Tololo Inter-American Observatory (CTIO) 4-meter telescope[4]. We have calculated the wavelength-to-mass sensitivity coefficients for a larger number of spectral lines and employed them in the analysis. A total of 59 transitions for H_2 are incorporated into the χ^2 fit, and the absorption lines corresponding to these transitions occur across the linear, saturated, and damped parts of the curve of growth. The redshift, Doppler parameter, and column densities of the H_2 rotational levels were adopted as free parameters.

A limit to variation of the proton-to-electron mass ratio was sought by repeating the χ^2 profile fitting analysis with an additional free parameter $\Delta\mu/\mu$.

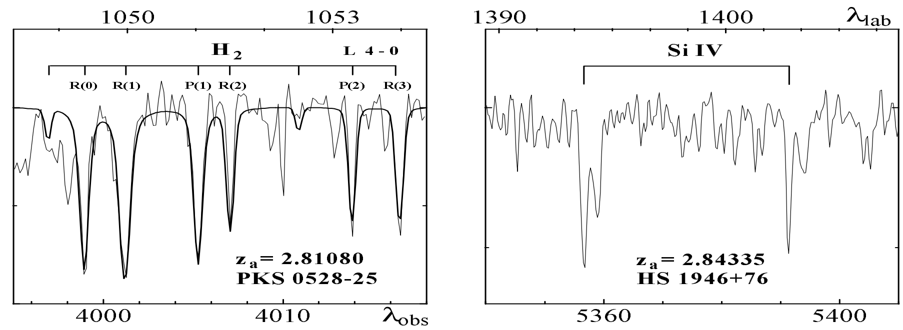

Figure 1: Fragments of QSO spectra obtained with CTIO (left) and SAO (right) telescopes and used for estimations of μ and α at the epochs z_a.

The resulting parameter estimate and 1σ uncertainty is

$$\Delta\mu/\mu = \left(8.3^{+6.6}_{-5.0}\right) \times 10^{-5}. \tag{2}$$

This result indicates a value of $\Delta\mu/\mu$ that differ from zero at the 1.6σ level. The 2σ confidence interval to $\Delta\mu/\mu$ is $(-0.2, +2.2) \times 10^{-4}$.

3 Fine-Structure Constant

Spectral observations of fine-splitted lines in quasar spectra provide the most direct test for variations of α. The relative splitting $(\Delta\lambda/\lambda)_z$ is proportional to α^2 at the redshift z. Therefore, the ratio

$$\frac{(\Delta\lambda/\lambda)_z}{(\Delta\lambda/\lambda)_0} \simeq 1 + 2\left(\frac{\Delta\alpha}{\alpha}\right) \tag{3}$$

would deviate from unity if the α value had changed.

In previous work [5], we have composed a catalogue of ~ 1500 alkali-like doublet wavelengths with $z > 0.2$ observed in the quasar absorption spectra, and obtained the restriction $|\Delta\alpha/\alpha| < 1.5 \times 10^{-3}$ at $z \sim 2.5$. In addition to the z-dependence of α averaged over the celestial sphere, we have also checked a possible spatial anisotropy of fine-splitting values at large z [6,1]. Within a relative statistical error $3\sigma < 0.3\%$ the values of α turned out to be the same in different celestial hemispheres, which corresponds to their equality in causally disconnected areas. However, at the 2σ level a tentative anisotropy of estimated fine-splitting values has been found.

In order to obtain a more stringent estimate of $\Delta\alpha/\alpha$, we have carried out new spectral observations of quasars with the Special Astrophysical Observatory (SAO) 6-meter telescope [7]. We have observed several absorption systems in spectra of HS 1946+76, S5 0014+81, and S4 0636+68. Fine-structure doublet wavelengths of Si IV were measured with high resolution and accurate calibration, using the same equipment and the same reduction procedures in order to obtain homogeneous data. The overall estimate at $z = 2.8 - 3.1$ reads

$$(\Delta\alpha/\alpha)_z = (2 \pm 7) \times 10^{-5}, \quad (4)$$

suggesting no statistically significant variation of α and providing the most stringent constraint to it.

4 Summary

Our analysis of QSO spectra reveals no statistically significant variation of the fine-structure constant $\alpha = e^2/\hbar c$ and the proton-to-electron mass ratio $\mu = m_p/m_e$. At the 2σ (95%-significance) level, the estimates (2) and (4) are obtained for the epoch corresponding to the cosmological redshifts $z \simeq 3.0$. These constraints are stronger than other recent astronomical[3] and laboratory[8] results, and they serve as effective criteria for selection of GUT and superstring models. In particular, they enable to exclude the Teller–Dyson hypothesis[9] of logarighmic time-dependence of the fine-structure constant.

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