Astronomy Letters, Vol. 22, No. 1, 1996, pp. 6–13. Translated from Pis'ma v Astronomicheskii Zhurnal, Vol. 22, Nos. 1–2, 1996, pp. 8–16.

Absorption Systems in the Spectra of the Quasars HS 1946+76, S5 0014+81, and S4 0636+68: New Bounds on Cosmological Change in the Fine-Structure Constant

D. A. Varshalovich*, V. E. Panchuk**, and A. V. Ivanchik*

*Ioffe Physicotechnical Institute, Russian Academy of Sciences, ul. Politekhnicheskaya 26, St. Petersburg, 194021 Russia

**Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz, Stavropol'skii krai, 357147 Russia

Received August 24, 1995

Abstract—In order to more accurately measure the fine splitting of resonance lines at an epoch corresponding to the redshift $z \approx 3$, we carried out spectroscopic observations of the QSOs HS 1946+76, S5 0014+81, and S4 0636+68 with resolution FWHM ≈ 20 km s^{-1}, which is high for quasars, and signal-to-noise ratio S/N ≈ 15 using the 6-m Special Astrophysical Observatory telescope. A study of multicomponent Si IV line profiles made it possible to determine kinematic properties of individual gas clouds in the galaxies that happened to be along the line of sight. An analysis of the relative fine splitting $\Delta\lambda/\lambda$ of the Si IV resonance lines in absorption spectra of the quasars has yielded a new constraint on the possible variation of the fine-structure constant $\alpha = e^2/\hbar c$ at the epoch of line formation $z = 2.8$–3.1:

$$(\Delta\alpha/\alpha)_z = (0.2 \pm 0.7) \times 10^{-4}.$$

The upper limit on the rate of change of α averaged over ~10 Gyr (at 2σ level) is

$$|\overline{\dot{\alpha}/\alpha}| < 1.6 \times 10^{-14}\ \mathrm{yr}^{-1}.$$

This constraint is more stringent than those obtained from previous astronomical observations and precise laboratory measurements.

INTRODUCTION

Analysis of the spectra of high-redshift QSOs provides a unique opportunity for studying the cosmological evolution of the Universe by direct astrophysical means.

The prime objective of this paper is to systematically study the profiles of Si IV absorption lines in the spectra of distant QSOs with the aim of searching for a possible cosmological change in the fine-structure constant (the reason why we chose the SI IV doublet is given below).

Current many-dimensional cosmologies—Kaluza–Klein models, superstring models, etc.—admit in principle and, moreover, predict variations in fundamental constants during the cosmological evolution (Damour and Polyakov 1994; Wu and Wang 1986; Marciano 1984; Chodos and Detweiler 1980).

The fine-structure constant $\alpha = e^2/\hbar c$ is the basic parameter of quantum electrodynamics. Presently, it is measured with a relative uncertainty of $\sim 7 \times 10^{-9}$. Laboratory measurements (a comparison of the frequencies of hyperfine transitions in hydrogen atoms and mercury ions) put an upper limit on the rate of possible change of α with time equal to $|\dot{\alpha}/\alpha| \le 3.7 \times 10^{-14}$ yr^{-1} (Prestage *et al.* 1995). However, a similar comparison of the frequencies of hyperfine transitions in hydrogen masers and cesium standards has revealed a systematic frequency drift, suggesting a change of α at the level given above (Breakiron 1993; Demidov *et al.* 1992). This fact makes this problem particularly acute and lends it a peculiar sense of urgency.

It should be noted that in contrast to precise laboratory measurements, which give estimates of $\dot{\alpha}/\alpha$ only for our epoch, astrophysical methods make it possible to estimate α at earlier evolutionary phases of the Universe and determine the relative rate of change of α by measuring the fine splitting of atomic and ionic resonance lines as a function of redshift z, i.e., cosmological time.

Quasar spectra show the absorption resonance lines of the ions C IV, N V, O VI, Mg II, Al III, and Si IV corresponding to the $S_{1/2} \longrightarrow P_{1/2}(\lambda_1)$ and $S_{1/2} \longrightarrow P_{3/2}(\lambda_2)$

1063-7737/96/2201-0006$10.00 © 1996 МАИК Наука/Interperiodica Publishing

transitions. The difference between λ_1 and λ_2 is due to the fine splitting of the $P_{1/2}$ and $P_{3/2}$ energy levels.

The relative magnitude of fine splitting of the corresponding resonance lines is proportional to the square of α^2,

$$\frac{\Delta\lambda}{\lambda} \propto \alpha^2,$$

where $\Delta\lambda = \lambda_1 - \lambda_2$ and $\lambda = (\lambda_1 + \lambda_2)/2$. Thus, the ratio $\frac{(\Delta\lambda/\lambda)_z}{(\Delta\lambda/\lambda)_0}$ is equal to $\left(\frac{\alpha_z}{\alpha_0}\right)^2$, where the subscripts z and 0 denote the fine-splitting doublet in a quasar spectrum and the laboratory value, respectively. Hence, the relative change in α can be written as

$$\left(\frac{\Delta\alpha}{\alpha}\right)_z = \frac{1}{2}\left[\left(\frac{\lambda_1-\lambda_2}{\lambda_1+\lambda_2}\right)_z \Big/ \left(\frac{\lambda_1-\lambda_2}{\lambda_1+\lambda_2}\right)_0 - 1\right].$$

Specifically, this formula takes the following form for Si IV (Table 1):

$$\left(\frac{\Delta\alpha}{\alpha}\right)_z = 155.11\left(\frac{\lambda_1-\lambda_2}{\lambda_1+\lambda_2}\right)_z - 0.5.$$

Since the redshift parameter z defined by relation $\lambda_{obs} = \lambda_0(1+z)$ is commonly used in spectroscopic studies of QSOs, the latter expression can be written as

$$\left(\frac{\Delta\alpha}{\alpha}\right)_z = 77.55\left(\frac{\Delta z}{1+\bar{z}}\right),$$

where $\Delta z = z_1 - z_2$, a $\bar{z} = (z_1 + z_2)/2$.

Thus, by measuring λ_1 and λ_2 in an absorption system corresponding to the redshift z and comparing the derived and laboratory values, one can directly estimate the difference between α at the epoch z and the present value.

This method was originally proposed by Savedoff (1956). Bahcall and Schmidt (1967) were the first to directly apply it to fine-splitting doublets in quasar spectra. A detailed analysis of this problem was performed by Potekhin and Varshalovich (1994), Levshakov (1994), and Varshalovich and Potekhin (1994).

OBSERVATIONS AND INITIAL REDUCTION OF SPECTRA

To solve our problem, we chose the brightest high-redshift QSOs whose spectra exhibit absorption systems containing fine-splitting doublets. Our aim was to remeasure the doublet wavelengths with higher resolution using the same equipment and the same reduction procedures to obtain the highest quality and most homogeneous data possible. For our analysis, we selected the Si IV line doublet (Table 1), because it has the highest ratio $\Delta\lambda/\lambda$ among the fine-splitting doublets observed in the quasar spectra (C IV, N V, O VI, Mg II, Al III, and Si IV), allowing this ratio to be measured most accurately.

We carried out our observations, summarized in Table 2, in 1994 using the main stellar spectrograph of the 6-m telescope. A Schmidt camera (F : 2.3), reconstructed to operate with a CCD array, was employed. In combination with a 600 lines mm^{-1} diffraction grating operating in second order, this camera yielded a linear reciprocal dispersion of 14 Å mm^{-1} (0.24 Å pixel^{-1}). The detector was a 530×580 pixel CCD array (Borisenko *et al.* 1991). The readout noise was 18 e^-, and the quantum efficiency amounted to 40% at the sensitivity maximum. The spectrum was 3 or 4 pixels high for an image diameter of 1 arcsec. The night-sky spectrum was taken at a distance as great as 20 arcsec on either side of the quasar spectrum. To allow for the possible contribution of the telluric spectrum and reveal any possible defects in the CCD array, we first took the spectrum of a rapidly rotating hot star. The same portion of the quasar spectrum was recorded several times in succession (with a 1-hour exposure each), which allowed us to increase the signal-to-noise ratio and effectively clean the image of cosmic rays.

We reduced our observations using a software package developed for the reduction of echelle spectra (Galazutdinov 1992). Since this study is metrological in nature, we paid special attention to wavelength calibration and check measurements. For our calibration, we employed a Th–Ar lamp and an atlas of the Th–Ar spectrum constructed from echelle data (D'Odorico *et al.* 1987), which gives vacuum wavelengths λ to within 0.001 Å. Ten to twenty reference lines were used to construct the dispersion curve in the form of a cubic polynomial for each of the spectral segments in question. Special attention was given to the nonlinear terms of the dispersion curve, because the accuracy of the measured ratio $\Delta\lambda/\lambda$ was particularly sensitive to the nonlinearity of the scale. For the same reason, the spectrograph was adjusted for each of the Si IV doublets in such a way that both doublet lines, with a separation of about 36 Å for $z \sim 3$, were in the middle of the spectral segment recorded corresponding to one order, where the nonlinear distortions of the scale were at a minimum, while the sensitivity was at a maximum.

In all cases, the dispersion curve was constructed with an uncertainty no greater than 0.001 Å. The actual accuracy of our λ determinations for the lines in the

Table 1. The fine-splitting doublet of the Si IV resonance lines

Transition	λ_0, Å	f_{abs}	E^*, eV	τ^*, 10^{-9} s
$S_{1/2}$–$P_{1/2}$	1402.7695	0.260	10.11	1.14
$S_{1/2}$–$P_{3/2}$	1393.7550	0.524	10.41	1.11

Note: The data of Kelly (1987) and Striganov and Odintsova (1982) were used to compile the table.

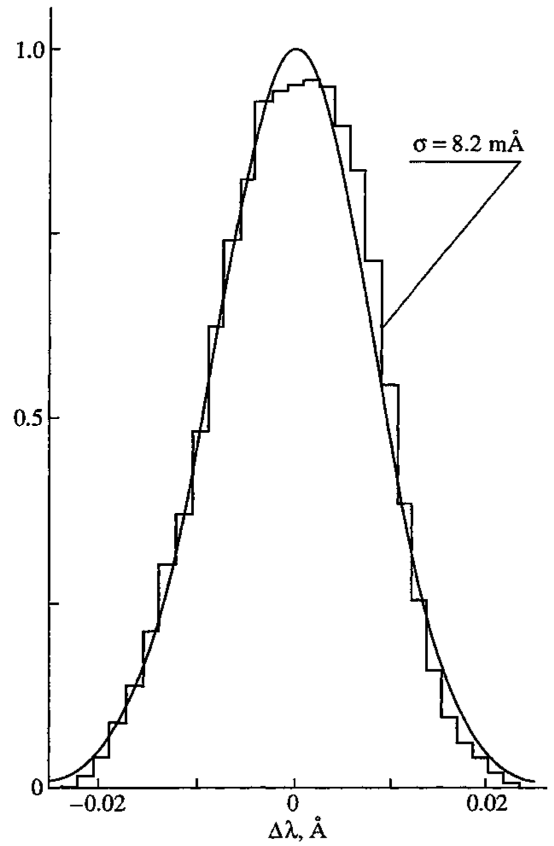

Fig. 1. Results of the check measurements. The distribution of deviations $\Delta\lambda$ of measured wavelengths λ_m from tabulated values λ_0.

calibration spectrum that were not used to construct the dispersion curve was 0.008 Å, i.e., 0.5 km s^{-1} at $\lambda = 5500$ Å (Fig. 1). For single unsaturated lines in the calibration spectrum, the full width at half maximum (FWHM) of the lines was ~0.38–0.40 Å, i.e., 20.7–21.8 km s^{-1}. The Gaussian parameter FWHM/$(2\sqrt{2\ln 2})$ equal to 0.16–0.17 Å, i.e., 8.5–9.3 km s^{-1}, which characterizes the spectral resolution, corresponds to this width. At the same time, the center of such a line can be determined with an accuracy as high as 0.007 Å, at a signal-to-noise ratio of ~30 consistent with the results of our check measurements.

Table 2. Log of observations

QSO	V	Date, October 1994	Coverage, Å	Exposure, s
HS 1946+76	$15^m.9$	10/11	5315–5440	4 × 3600
HS 1946+76	15.9	11/12	5600–5725	2 × 3600
S5 0014+81	16.5	10/11	5260–5385	4 × 3600
S4 0636+68	16.4	10/11	5405–5530	1 × 3600

The accuracy of λ determination in the quasar spectrum for a signal-to-noise ratio of ~ 15 is then 0.015 Å, i.e., 0.8 km s^{-1}, so that the relative uncertainty in λ for an individual line must be of the order of 2.7×10^{-6}.

RESULTS OF OBSERVATIONS AND THEIR ANALYSIS

Portions of the quasar spectra containing the Si IV doublets are shown in Figs. 2–5. Table 3 gives the measured wavelengths of these doublets.

Absorption systems containing lines of heavy elements appear to be formed in interstellar-gas clouds within galaxies happened to be along the line of sight from observer to quasar. In view of this, absorption profiles commonly have a few components with close velocities whose differences are typical of the relative velocities of clouds in the galaxy. Figure 6 shows the profile of such an absorption system in which we identified four components. They can be interpreted in terms of four clouds with different column densities and a scatter in radial velocities of ~170 km s^{-1}. In this case, the combined line profile depends on the individual properties of each cloud and is given by the following formula:

$$I(\lambda) = I_0(\lambda)\exp\left(-\sum_{i=1}^{4}\tau_i(\lambda)\right),$$

$$\text{where } \tau_i(\lambda) = \tau_{0i}\exp\left(-\frac{(\lambda_{0i}-\lambda)^2}{b_i^2}\right).$$

Here, τ_{0i} is the cloud optical depth at the center of the line with central wavelength λ_{0i}, and b_i is the Doppler parameter of the cloud. We determined these parameters by minimizing the χ^2 value for the fitting profile. The parameters τ_{0i} and b_i are sensitive to the choice of the continuum, while λ_{0i}, which is essential for our analysis, depends only slightly on the choice of the continuum and variations in the parameters for strong components.

It should be emphasized that the above interpretation of the profile is valid in the microturbulent limit, but other interpretations determined by the nature of absorbing clouds in principle are also possible.

Portions of the spectrum of HS 1946+76 $z_{em} = 3.05$, one of the brightest QSOs, are shown in Figs. 2 and 3. In their recent analysis of the spectrum of this quasar, Fan and Tytler (1994) have detected six absorption systems, two of which contain Si IV lines. However, they measured only one of the doublet components in each of the doublets. In Fig. 7, the profiles of our measured spectral lines are compared with the profile obtained by Fan and Tytler with a resolution of ~10 km s^{-1}. The double structure of the less saturated N V ($\lambda_0 = 1238$ Å) and Si II ($\lambda_0 = 1260$ Å) lines reveals the presence of two components. A comparison of the profiles indicates that

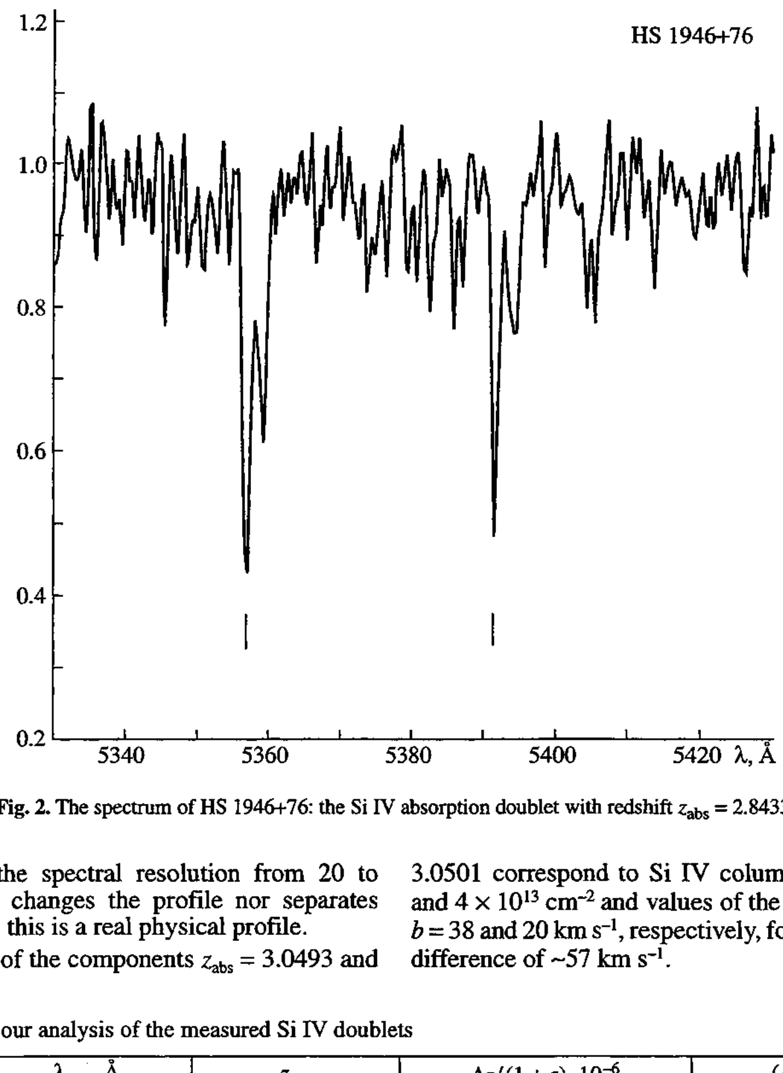

Fig. 2. The spectrum of HS 1946+76: the Si IV absorption doublet with redshift z_{abs} = 2.8433.

since increasing the spectral resolution from 20 to 10 km s^{-1} neither changes the profile nor separates these components, this is a real physical profile.

The properties of the components z_{abs} = 3.0493 and 3.0501 correspond to Si IV column densities of 10^{14} and 4×10^{13} cm^{-2} and values of the Doppler parameter $b = 38$ and 20 km s^{-1}, respectively, for a relative velocity difference of ~57 km s^{-1}.

Table 3. Results of our analysis of the measured Si IV doublets

QSO	λ_{obs}, Å	z_{abs}	$\Delta z/(1+z)$, 10^{-6}	$(\Delta\alpha/\alpha)_z$, 10^{-4}
HS 1946+76	5681.333 5644.812	3.050083 3.050075	2.04	1.58
HS 1946+76	5680.252 5643.747	3.049312 3.049311	0.44	0.34
S4 0636+64	5477.157 5441.950	2.904531 2.904524	1.77	1.37
HS 1946+76	5391.347 5356.697	2.843359 2.843356	0.76	0.59
S5 0014+81	5332.420 5298.165	2.801352 2.801360	−2.32	−1.80
S5 0014+81	5331.696 5297.445	2.800835 2.800844	−2.20	−1.70
S5 0014+81	5330.569 5296.306	2.800032 2.800027	1.44	1.11
	$\delta\lambda = 0.012$ Å $\sigma(\lambda) = 0.008$ Å	$\delta z = 8.7 \times 10^{-6}$ $\sigma(z) = 5.8 \times 10^{-6}$	$\overline{\Delta z/(1+z)} = 0.28 \times 10^{-6}$ $\sigma(\Delta z/(1+z)) = 1.82 \times 10^{-6}$	$\overline{(\Delta\alpha/\alpha)_z} = 0.21 \times 10^{-4}$ $\sigma(\Delta\alpha/\alpha) = 1.41 \times 10^{-4}$

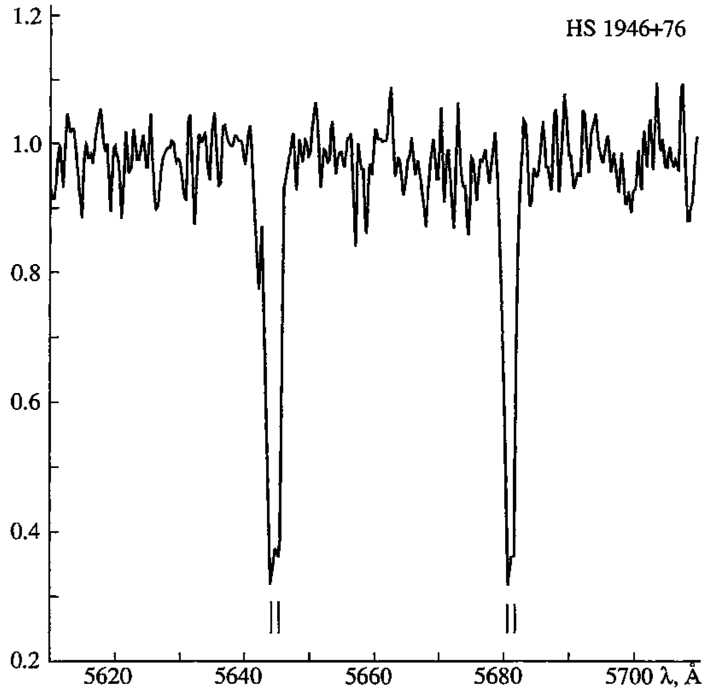

Fig. 3. The spectrum of HS 1946+76: The double structure of the Si IV absorption doublet with redshifts z_{abs} = 3.0493 and 3.0501.

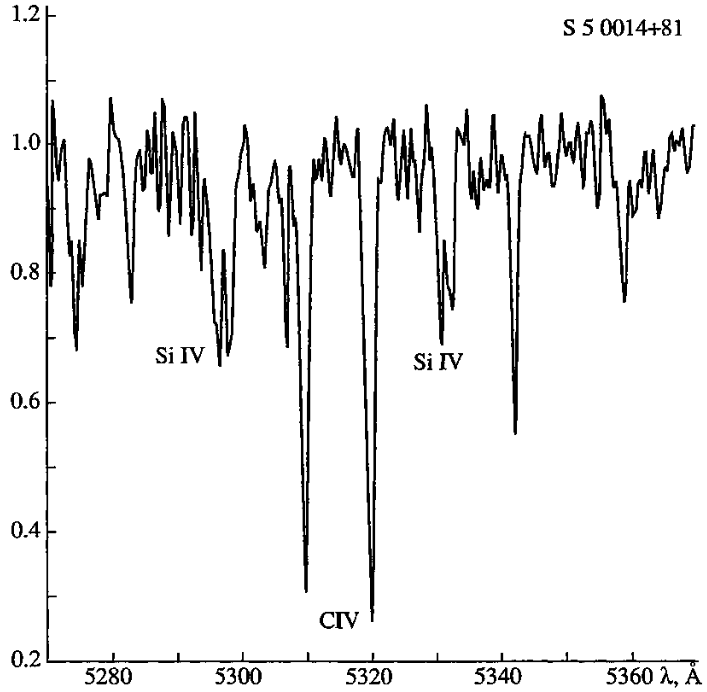

Fig. 4. The spectrum of S 5 0014+81: the absorption doublets of C IV (λ_0 = 1548 and 1550 Å) with z_{abs} = 2.429 and Si IV (λ_0 = 1393 and 1402 Å) with z_{abs} = 2.800–2.801 whose lines show a multicomponent profile (see Fig. 6).

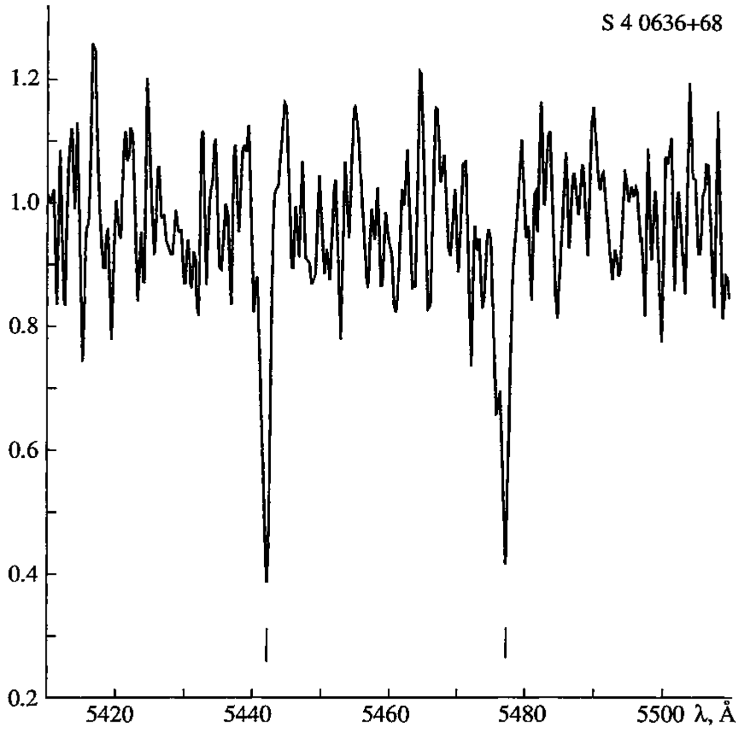

Fig. 5. The spectrum of S 4 0636+68: the Si IV absorption doublet with redshift $z_{abs} = 2.9045$.

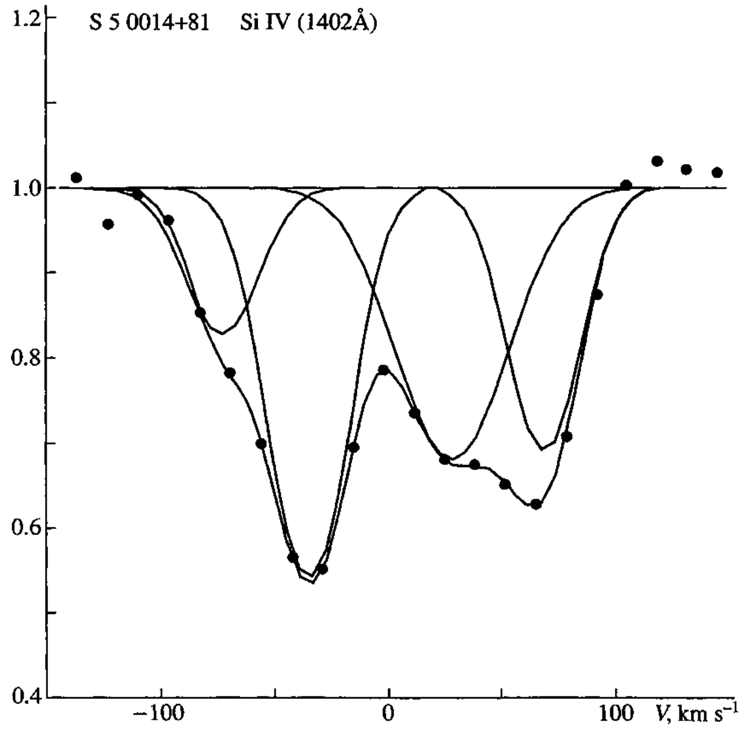

Fig. 6. The spectrum of S 5 0014+81: the multicomponent structure of the Si IV $\lambda_0 = 1402$ Å line in the complex $z_{abs} = 2.800$–2.801.

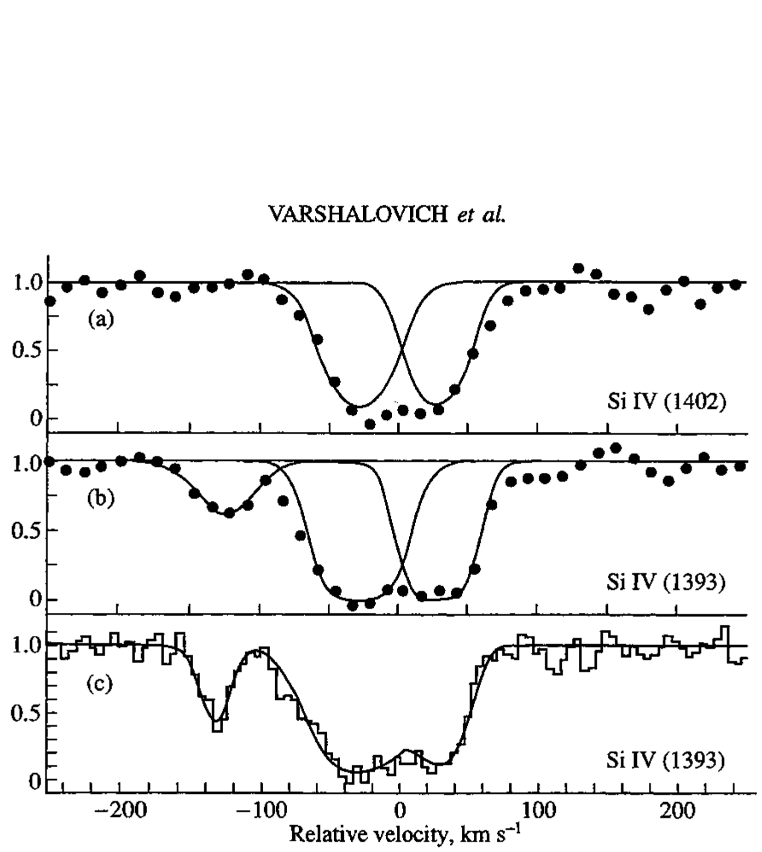

Fig. 7. The spectrum of HS 1946+76: comparison of the profiles of the Si IV doublet absorption lines with z_{abs} = 3.049–3.050 [the λ_0 = 1393 Å (a) and 1402 Å (b) lines in our study and the λ_0 = 1402 Å line (c) in Fan and Tytler (1994)].

The final wavelengths of the Si IV fine-splitting doublet lines and results of their analysis are presented in Table 3. The accuracy of the tabulated values of λ_{obs} (with respect to the heliocentric reference frame) is 0.015 Å; it includes both the random statistical error $\sigma_\lambda \approx 0.008$ Å and the error $\delta_\lambda = 0.012$ Å corresponding to the correlated shift in λ_{obs} of both doublet lines. The correlation coefficient of the deviations of the measured λ_1 and λ_2 turns out to be 0.76. Therefore, the accuracy of determination of individual z_{abs} is $\sigma_z \sim 0.9 \times 10^{-5}$, whereas that of the ratio $\Delta z/(1 + \bar{z})$ is $\sigma(\Delta z/(1 + \bar{z})) \approx 1.8 \times 10^{-6}$. Accordingly, $(\Delta\alpha/\alpha)_z$ defined by the relation $\frac{1}{2}\left[\frac{(\Delta\lambda/\lambda)_z}{(\Delta\lambda/\lambda)_0} - 1\right]$ is estimated from measurements of a single doublet with an accuracy of $\sigma(\Delta\alpha/\alpha) \sim 1.4 \times 10^{-4}$ is estimated from seven doublets to be $(\Delta\alpha/\alpha) = (0.2 \pm 0.6) \times 10^{-4}$. Given that the values of $(\Delta\alpha/\alpha)$ corresponding to close doublets could be partially dependent, the number of independent systems is four. Thus, the majorizing estimate is

$$\left(\frac{\Delta\alpha}{\alpha}\right)_{z=3} = (0.2 \pm 0.7) \times 10^{-4}.$$

The upper limit on the mean rate of change of α with increasing z (at the 2σ level) is then

$$\left|\frac{1}{\alpha}\frac{d\alpha}{dz}\right| < 5.3 \times 10^{-5}.$$

According to the current cosmological model, the time elapsed since the formation of the absorption spectrum with $z \approx 3$ is $t_0[1 - (1 + z)^{-3/2}] \approx 0.87t_0$ for $\Omega = 1$ or $t_0[1 - (1 + z)^{-1}] \approx 0.75t_0$ for $\Omega z \ll 1$, where t_0 is the present age of the Universe, $(1.5 \pm 0.3) \times 10^{10}$ yr, and Ω is the mean-to-critical density ratio. Thus, the majorizing estimate of the upper limit on the time-averaged rate of change of α is

$$\left|\frac{1}{\alpha}\frac{d\alpha}{dt}\right| < 1.6 \times 10^{-14}\ \text{yr}^{-1}.$$

CONCLUSION

We have obtained quasar spectra on the 6-m Special Astrophysical Observatory telescope with resolution FWHM ~ 20 km s^{-1} high enough for metrological measurements to be performed. This level of resolution sets a new standard.

An analysis of the measured wavelengths of the Si IV fine-splitting doublet lines at $z \approx 3$ yielded the most stringent upper bound on the rate of cosmological change of the fine-structure constant α (at the 2σ level),

$$|(\Delta\alpha/\alpha)_z| < 1.6 \times 10^{-4} \text{ for } z \approx 2.8\text{–}3.1.$$

This estimate corresponds to the following limit on the rate of possible change of α averaged over 10 Gyr:

$$|\overline{\dot{\alpha}/\alpha}| < 1.6 \times 10^{-14}\ \text{yr}^{-1}.$$

This constraint is more stringent than that obtained in previous astronomical observations (Varshalovich and Potekhin 1994; Cowie *et al.* 1995) and precise laboratory measurements (Godone *et al.* 1993; Prestage *et al.* 1995).

ACKNOWLEDGMENTS

We are grateful to V.G. Klochkova for analysis of the observational variant described above, G.A. Galazutdinov for advice on how to use the reduction package for stellar spectra, and A.D. Kaminker for assistance in the observations and helpful discussions. We also wish to thank S.A. Levshakov and A.Yu. Potekhin for their helpful remarks. This study was supported by the Russian Foundation for Basic Research (project no. 93-02-02958a), the International Science Foundation (grant no. NUO 000/300), and the Cosmion Research Center.

REFERENCES

Bahcall, J.N. and Schimdt, M., *Phys. Rev. Lett.*, 1967, vol. 19, p. 1294.

Borisenko, A.N., Markelov, S.V., and Ryadchenko, V.P., A Virtual Phase CCD in the Image System for Spectral Observations on the 6-m Telescope, *Preprint of Spec. Astrophys. Obs.*, 1991, no. 76.

Breakiron, L.A., *Proc. 25th Ann. Precise Time Interval Applications and Planning Meet.*, NASA Conf. Publ. no. 3267, 1993, p. 401.

Chodos, A. and Detweiler, S., *Phys. Rev.*, 1980, vol. D21, p. 2167.

Cowie, L.L. and Songaila, A., *Astrophys. J.*, 1995 (in press).

Damour, T. and Polyakov, A.M., *Nucl. Phys.*, 1994, vol. B423, p. 532.

Demidov, N.A., Ezhov, E.M., Sakharov, B.A., *et al.*, *Proc. 6th European Frequency and Time Forum*, ESA, 1992, p. 409.

D'Odorico, S., Ghigo, M., and Ponz, D., An Atlas of the Thorium–Argon Spectrum for the ESO Echelle Spectrograph in the $\lambda\lambda$ 3400–9000 Å Region, *ESO Scientific Rep.*, 1987, no. 6.

Fan, X.-M. and Tytler, D., *Astrophys. J., Suppl. Ser.*, 1994, vol. 94, p. 17.

Galazutdinov, G.A., Reduction Package for Stellar Echelle Spectra, *Preprint of Spec. Astrophys. Obs.*, 1992, no. 92.

Godone, A., Novero, C., Travella, P., and Rahimullah, K., *Phys. Rev. Lett.*, 1993, vol. 71, p. 2364.

Kelly, R.L., Atomic and Ionic Spectrum Lines below 2000 Å, *J. Phys. Chem. Ref. Data NBS*, 1987, vol. 16, Suppl. 1.

Marciano, W.J., *Phys. Rev. Lett.*, 1984, vol. 52, p. 489.

Potekhin, A.Yu. and Varshalovich, D.A., *Astron. Astrophys., Suppl. Ser.*, 1994, vol. 104, p. 89.

Prestage, J.D., Tjoelker, R.L., and Maleki, L., *Phys. Rev. Lett.*, 1995, vol. 74, p. 3511.

Savedoff, M.P., *Nature*, 1956, vol. 178, p. 688.

Sargent, W.L.W., Steidel, C.C., and Boksenberg, A., *Astrophys. J., Suppl. Ser.*, 1989, vol. 69, p. 703.

Striganov, A.R. and Odintsova, G.A., *Tablitsy spektral'nykh linii atomov i ionov* (Tables of Atomic and Ionic Spectral Lines), Moscow: Energoizdat, 1982.

Varshalovich, D.A. and Potekhin, A.Yu., *Astron. Lett.*, 1994, vol. 20, p. 771.

Wu, Y. and Wang, Z., *Phys. Rev. Lett.*, 1986, vol. 57, p. 1978.