Problems of Cosmological Variability of Fundamental Physical Constants*

D. A. Varshalovich, A. Y. Potekhin and A. V. Ivanchik
Ioffe Physical-Technical Institute, 194021 St. Petersburg, Russia

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Abstract

We discuss recent laboratory experiments and astronomical observations aimed at testing the possible space-time variability of fundamental physical constants, predicted by the modern theory. Specifically, we consider two of the dimensionless physical parameters which are important for atomic and molecular physics: the fine-structure constant α and the electron-to-proton mass ratio μ. We review the current status of such experiments and critically analyze recent claims of a detection of the variability of the fine-structure constant on the cosmological time scale. We stress that such a detection remains to be checked by future experiments and observations. The tightest of the firmly established upper limits, derived from analyses of quasar spectra formed at the early cosmological epoch ($\sim 10^{10}$ yr ago), read: $|\dot{\alpha}/\alpha| < 1.1 \times 10^{-14}$ yr^{-1}, $|\dot{\mu}/\mu| < 1.5 \times 10^{-14}$ yr^{-1}. These limits may be used as an effective tool for selection of theoretical models which predict space-time variations of physical constants.

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1. Introduction

A fundamental role in the atomic and molecular spectroscopy is played by small dimensionless constants (such as the fine-structure constant $\alpha = e^2/\hbar c$ or the electron-to-proton mass ratio $\mu = m_e/m_p$) which allow to use the perturbation theory and to separate different types of contributions in the spectra. The modern theory (Supersymmetric Grand Unification Theory – SUSY GUT, Superstring/M-brane models, etc.) has established that the coupling constant values which characterize different kinds of interactions (i) are "running" with the energy transfer and (ii) may be different in different regions of the Universe and vary in the course of cosmological evolution (e.g., Ref. [1]). The energy dependence of the coupling parameters has been reliably confirmed by high-energy experiments (for example, α equals 1/137.036 at low energy and 1/128.897 at the energy 91 GeV – see, e.g., Ref. [2]), whereas the space-time variability of their low-energy limits so far escapes detection. In this paper we focus on the latter kind of variability – the variability of the low-energy limits of the fundamental constants which govern most of the common phenomena and are usually given in the handbooks.

Note that a numerical value of any dimensional physical parameter depends on arbitrary choice of physical units. In turn, there is no way to determine the units in a remote space-time region other than through the fundamental constants. Therefore it is meaningless to speak of a variation of a dimensional physical constant without specifying which of the other physical parameters are

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defined to be invariable. Thus, only *dimensionless* combinations of the physical parameters are truly fundamental, and only such combinations will be considered hereafter.

At present, the most promising candidate for the theory which is able to unify gravity with all other interactions is the Superstring theory, which treats gravity in a way consistent with quantum mechanics. All versions of the theory predict existence of the dilaton – a scalar partner to the tensorial graviton. Since the dilaton field ϕ is generally non-constant, the coupling constants and masses of elementary particles, being dependent on ϕ, should vary in space and time. Thus, the existence of a weakly coupled massless dilaton entails small, but non-zero, observable consequences such as Jordan–Brans–Dicke-type deviations from General Relativity and cosmological variations of the gauge coupling constants [7]. These variations depend on cosmological evolution of the dilaton field and may be non-monotonous as well as different in different space-time regions. It has been shown that this generalized theory tends to the usual General Relativity in course of the cosmological evolution, but the deviations could be large at the early stage.

Thus, the (non)variability of fundamental constants has to be checked experimentally. Even a reliable upper limit on a possible variation rate of a physical constant can be very important for selection of viable theoretical models.

The next section presents a compendium of the basic methods allowing one to obtain restrictions on possible variations of fundamental constants. In Sects. 3. and 4., we consider recent estimates of the values of α and μ, respectively, at epochs $\sim$ 7–13 billion years ago. Conclusions are given in Sect. 5..

2. Tests of variability of fundamental constants

Techniques used to investigate time variation of the fundamental constants may be divided into extragalactic and local methods. The latter ones include astronomical methods related to the Galaxy and the Solar system, geophysical methods, and laboratory measurements.

2.1. Local tests

2.1.1. Laboratory measurements

Laboratory tests are based on comparison of different frequency standards, depending on different combinations of the fundamental constants. Were these combinations changing differently, the frequency standards would eventually discord with each other. An interest in this possibility has been repeatedly excited since relative frequency drift was observed by several research groups using long term comparisons of different frequency standards. For instance, a comparison of frequencies of He-Ne/CH_4 lasers, H masers, and Hg^+ clocks with a Cs standard [8, 9, 10, 11] has revealed relative drifts. Since the considered frequency standards have a different dependence on α via relativistic contributions of order α^2, the observed drift might be attributed to changing of the fine-structure constant. However, the more modern was the experiment, the smaller was the drift. Taking into account that the drift may be also related to some aging processes in experimental equipment, Prestage et al. [11] concluded that the current laboratory data provide only an upper limit $|\dot{\alpha}/\alpha| \leq 3.7 \times 10^{-14}$ yr^{-1}. This conclusion has been confirmed by the most recent and accurate measurements [38], based on a comparison of ^{133}Cs and ^{87}Rb frequency standards. In this experiment, the frequency of the ground-state HFS transition of ^{87}Rb, $\nu_{\rm HFS}({\rm Rb}) = 6\,834\,682\,610.904\,343$ (17) Hz, was compared with that of ^{133}Cs, which is presently adopted as the metrological standard: $\nu_{\rm HFS}({\rm Cs}) = 9\,192\,631\,770$ Hz. During about three years, no statistically significant change of the ratio of these frequencies was detected:

$$\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\frac{\nu_{\rm HFS}({\rm Rb})}{\nu_{\rm HFS}({\rm Cs})}\right) = \frac{\dot{g}_{\rm Rb}}{g_{\rm Rb}} - \frac{\dot{g}_{\rm Cs}}{g_{\rm Cs}} - 0.45\frac{\dot{\alpha}}{\alpha} = (1.9 \pm 3.1) \times 10^{-15}\ {\rm yr}^{-1}, \tag{1}$$

where g is the gyromagnetic ratio of the nucleus. Assuming that $g_{\rm Rb}$ and $g_{\rm Cs}$ are constant, one arrives at the estimate

$$\dot{\alpha}/\alpha = (-4.2 \pm 6.9) \times 10^{-15}\ {\rm yr}^{-1}, \qquad (2)$$

which can be considered as the most stringent laboratory constraint on the time-variation of α. On the other hand, Eq. (1) can be also considered as a constraint on the time-variability of the gyromagnetic ratios.

2.1.2. Analysis of the Oklo phenomenon

Strong limits to variation of the fine-structure constant α and the coupling constant of the strong interaction α_s have been originally inferred by Shlyakhter [12] from results of an analysis of the isotope ratio ^{149}Sm/^{147}Sm in the ore body of the Oklo site in Gabon, West Africa. This ratio (0.006) turned out to be considerably lower than the standard one (0.92), which is believed to have occurred due to operation of the natural uranium fission reactor about 2×10^9 yr ago in those ores. One of the nuclear reactions in the fission chain was the resonance capture of neutrons by ^{149}Sm nuclei. Actually, the rate of the neutron capture reaction is sensitive to the energy of the relevant nuclear resonance level E_r, whose position depends on the strong and electromagnetic interaction. Since the capture has been efficient 2×10^9 yr ago, in means that the position of the resonance has not shifted by more than it width (very narrow) during the elapsed time. At variable α and invariable α_s (which is just a model assumption), the shift of the resonance level would be determined by changing the difference between the Coulomb energies of the ground-state nucleus ^{149}Sm and the nucleus ^{150}Sm* excited to the level E_r. Unfortunately, there is no experimental data for the Coulomb energy of the excited ^{150}Sm* in question. Using order-of-magnitude estimates, Shlyakhter [12] concluded that $|\dot{\alpha}/\alpha| \lesssim 10^{-17}$ yr^{-1}. From an opposite model assumption that α_s is changing whereas α =constant, he derived a bound $|\dot{\alpha}_s/\alpha_s| \lesssim 10^{-19}$ yr^{-1}.

Damour and Dyson [13] performed a more careful analysis, which resulted in the upper bound $|\dot{\alpha}/\alpha| \lesssim 7 \times 10^{-17}$ yr^{-1}. They have assumed that the Coulomb energy difference between the nuclear states of ^{149}Sm and ^{150}Sm* in question is not less than that between the *ground* states of ^{149}Sm and ^{150}Sm. The latter energy difference has been estimated from isotope shifts and equals ≈ 1 MeV. However, it looks unnatural that a weakly bound neutron (≈ 0.1 eV), captured by a ^{149}Sm nucleus to form the highly excited state ^{150}Sm*, can so strongly affect the Coulomb energy. Moreover, heavy excited nuclei often have Coulomb energies smaller than those for their ground states (e.g., Ref. [14]). This indicates the possibility of violation of the basic assumption involved in Ref. [13], and therefore this method may possess a lower actual sensitivity. Furthermore, a correlation between α and α_s (which is likely in the frame of modern theory) might lead to considerable softening of the above-mentioned bound, as estimated by Sisterna and Vucetich [15].

2.1.3. Some other local tests

Geophysical, geochemical, and paleontological data impose constraints on a possible changing of various combinations of fundamental constants over the past history of the Solar system, however most of these constraints are very indirect. A number of other methods are based on stellar and planetary models. The radii of the planets and stars and the reaction rates in them are influenced by values of the fundamental constants, which offers a possibility to check variability of the constants by studying, for example, lunar and Earth's secular accelerations. This was done using satellite data, tidal records, and ancient eclipses. Another possibility is offered by analyzing the data on binary pulsars and the luminosity of faint stars. Most of these have relatively low sensitivity. Their common weak point is the dependence on a model of a fairly complex phenomenon, involving many physical effects.

An analysis of natural long-lived α- and β-decayers in geological minerals and meteorites is much more sensitive. For instance, a strong bound, $|\dot{\alpha}/\alpha| < 5 \times 10^{-15}$ yr^{-1}, was obtained by Dyson [16] from an isotopic analysis of natural α- and β-decay products in Earth's ores and meteorites.

Having critically reviewed the wealth of the local tests, taking into account possible correlated synchronous changes of different physical constants, Sisterna and Vucetich [15] derived restrictions on possible variation rates of individual physical constants for ages t less than a few billion years ago. In particular, they have arrived at the estimate $\dot{\alpha}/\alpha = (-1.3 \pm 6.5) \times 10^{-16}$ yr^{-1}.

All the local methods listed above give estimates for only a narrow space-time region around the Solar system. For example, the epoch of the Oklo reactor (1.8×10^9 years ago). These tests cannot be extended to earlier evolutionary stages of the Universe, because the possible variation of the fundamental constants is, in general, unknown and may be oscillating [17, 7]. Another investigation is needed for greater spacetime scales.

2.2. Extragalactic tests

Extragalactic tests, in contrast to the local ones, concern values of the fundamental constants in distant areas of the early Universe. A test which relates to the earliest epoch is based on the standard model of the primordial nucleosynthesis. The amount of ^{4}He produced in the Big Bang is mainly determined by the neutron-to-proton number ratio at the freezing-out of n$\leftrightarrow$p reactions. The freezing-out temperature T_f is determined by the competition between the expansion rate of the Universe and the β-decay rate. A comparison of the observed primordial helium mass fraction, $Y_p = 0.24 \pm 0.01$, with a theoretical value allows one to obtain restrictions on the difference between the neutron and proton masses at the epoch of the nucleosynthesis and, through it, to estimate relative variation of the curvature radius R of extra dimensions in multidimensional Kaluza–Klein-like theories which in turn is related to the α value [18, 19]. However, as noted above, different coupling constants might change simultaneously. For example, increasing the constant of the weak interactions G_F would cause a weak freezing-out at a lower temperature, hence a decrease in the primordial ^{4}He abundance. This process would compete with the one described above, therefore, it reduces sensitivity of the estimates. Finally, the restrictions would be different for different cosmological models since the expansion rate of the Universe depends on the value of the cosmological constant Λ at that epoch.

The most unambiguous estimation of the atomic and molecular constants at early epochs and in distant regions of the Universe can be performed using the extragalactic spectroscopy. Accurate measurements of the wavelengths in spectra of distant objects provide quantitative constraints on the variation rates of the physical constants. This opportunity has been first noted and used by Savedoff [20], and in recent years exploited by many researchers (see, e.g., Refs. [21, 22] and references therein). Because of the expansion of the Universe, distant objects recede from us at a great speed. As a result, the wavelengths of the spectral lines observed in radiation from these objects ($\lambda_{\rm obs}$) increase compared to the laboratory values ($\lambda_{\rm lab}$) in proportion $\lambda_{\rm obs} = \lambda_{\rm lab}(1+z)$, where z is the *cosmological redshift* which can be used to determine the age of the Universe at the line-formation epoch. Analyzing these spectra we, like a time-machine, may study the epochs when the Universe was several times younger than now. At present, the extragalactic spectroscopy enables one to probe the physical conditions in the Universe up to cosmological redshifts $z \lesssim 5$, which correspond, by order of magnitude, to the scales $\lesssim$ 15 Gyr in time and $\lesssim$ 5 Gpc in space. The large time span enables us to obtain quite stringent estimates of the rate of possible time variations, even though the astronomical wavelength measurements are not so accurate as the precision metrological experiments. Moreover, such analysis allows us to study the physical conditions in distant regions of the Universe, which were causally disconnected at the line-formation epoch. In the following sections, we review briefly the studies of the space-time variability of the fine-structure constant α and the electron-to-proton mass ratio μ, based on the latter method.

3. Upper limit on variability of α

Bahcall and Schmidt [23] were the first to use spectral observations of distant quasars to set a bound on the variability of the fine-structure constant. They have obtained an estimate $\Delta\alpha/\alpha = (-2 \pm 5) \times 10^{-2}$ at $z = 1.95$. Modern observations [22, 27] provide an accuracy which is better by approximately three orders of magnitude, compared to those pioneering measurements.

Quite recently, Webb et al. [27] have estimated α by comparing wavelengths of Fe II and Mg II fine-splitted spectral lines in extragalactic spectra and in the laboratory. The authors' estimate reads $\Delta\alpha/\alpha = (-1.9 \pm 0.5) \times 10^{-5}$ at $z = 1.0$–1.6. Note, however, two important sources of a possible systematic error which could mimic the effect: (a) Fe II and Mg II lines used are situated in different orders of the echelle-spectra, so relative shifts in calibration of the different orders can affect the result of comparison, and (b) if the isotopic composition varies during the evolution of the Universe, then the average doublet separations should vary due to the isotopic shifts. Were the relative abundances of Mg isotopes changing during the cosmological evolution, the Mg II lines would be subject to an additional z-dependent shift relative to the Fe II lines, quite sufficient to simulate the variation of α (this shift can be easily estimated from recent laboratory measurements [28]). In principle, however, the suggested method allows to attain a high accuracy, provided that the various sources of possible systematical errors are properly taken into account.

The method based on the fine splitting of a line of the same ion species is not affected by the two aforementioned uncertainty sources. We have studied the fine splitting of the doublet lines of Si IV, C IV, Mg II and other ions, observed in spectra of distant quasars, separately for each doublet type. According to quantum electrodynamics, the relative splitting of these lines $\delta\lambda/\lambda$ is proportional to α^2 (neglecting small relativistic corrections, recently estimated by Dzuba et al. [29]). We have selected the results of high-resolution observations [30, 31, 32], most suitable for an analysis of the variation of α. A typical high-resolution quasar spectrum containing several redshifted Si IV doublet lines is shown in Fig. 1. This spectrum has been obtained in frames of the Hubble Deep Field – South International project and is publicly available via Internet (URL `http://www.ast.cam.ac.uk/AAO/hdfs/`). According to our analysis, presented elsewhere [33], the most reliable estimate of the possible deviation of the fine-structure constant at $z = 2$–4 from its present ($z = 0$) value:

$$\Delta\alpha/\alpha = (-4.6 \pm 4.3\,[\mathrm{stat}] \pm 1.4\,[\mathrm{syst}]) \times 10^{-5}. \tag{3}$$

Thus, only an upper bound can be derived at present for the long-term variability of α. Assuming that the typical time $\approx 1.2 \times 10^{10}$ yr elapsed since the spectral lines were formed, we obtain

$$|\dot{\alpha}/\alpha| < 1.1 \times 10^{-14}\ \mathrm{yr}^{-1} \tag{4}$$

(at the 95% confidence level).

4. Upper limit on variability of μ

The dimensionless Born–Oppenheimer constant $\mu = m_e/m_p$ approximately equals the ratio of the constant of electromagnetic interaction $\alpha = e^2/\hbar c \approx 1/137$ to the constant of strong interaction $\alpha_s = g^2/\hbar c \sim 14$, where g is the effective coupling constant calculated from the amplitude of π-meson–nucleon scattering at low energy.

A precise analysis of a variation of μ has become possible due to discovery [36] of a system of H_2 absorption lines in the spectrum of quasar PKS 0528−250 at $z = 2.811$. Fragments of this spectrum (from Ref. [37]) containing the H_2 lines are shown in Fig. 2. A study of this system yields information about physical conditions and, in particular, the value of μ at this redshift (corresponding to the epoch when the Universe was several times younger than now). A possibility of distinguishing between the cosmological redshift of spectral wavelengths and shifts due to a variation of μ arises from the fact that the electronic, vibrational, and rotational energies of H_2 each undergo a different dependence on the reduced mass of the molecule. Hence comparing ratios of wavelengths λ_i of various H_2 electron-vibration-rotational lines in a quasar spectrum at some redshift z and in laboratory (at $z = 0$), we can trace variation of μ. We have calculated [21, 37] sensitivity coefficients K_i of the wavelengths λ_i with respect to possible variation of μ,

$$K_i = \frac{\mu}{\lambda_i}\frac{\mathrm{d}\lambda_i}{\mathrm{d}\mu}, \tag{5}$$

and applied a linear regression analysis to the measured redshifts of individual lines z_i as function of K_i. If the proton mass in the epoch of line formation were different from the present value, the measured z_i and K_i values would correlate:

$$\frac{z_i}{z_k} = \frac{(\lambda_i/\lambda_k)_z}{(\lambda_i/\lambda_k)_0} \simeq 1 + (K_i - K_k)\left(\frac{\Delta\mu}{\mu}\right). \tag{6}$$

We have performed a z-to-K regression analysis using a modern high-resolution spectrum of PKS 0528−250. Eighty-two of the H_2 lines have been identified. The resulting parameter estimate and 1σ uncertainty is [37]

$$\Delta\mu/\mu = (11.5 \pm 7.6\,[\mathrm{stat}] \pm 1.9\,[\mathrm{syst}]) \times 10^{-5}. \tag{7}$$

The 2σ confidence bound on $\Delta\mu/\mu$ reads

$$|\Delta\mu/\mu| < 2.0 \times 10^{-4}. \tag{8}$$

Assuming that the age of the Universe is $\sim 1.5 \times 10^{10}$ yr the redshift of the H_2 absorption system $z = 2.81080$ corresponds to the elapsed time $\approx 1.3 \times 10^{10}$ yr (in the current cosmological model). Therefore we arrive at the restriction

$$|\dot{\mu}/\mu| < 1.5 \times 10^{-14}\ \mathrm{yr}^{-1} \tag{9}$$

on the variation rate of μ, averaged over 90% of the lifetime of the Universe. This is the most strong and reliable upper limit on the μ variation.

5. Conclusions

Contemporary experiments and astronomical observations give negative answers to the two questions posed by the modern physics: Are the fundamental physical constants changing in the course of cosmological evolution? Are they values different in remote, causally disconnected regions of the Universe? In this paper we have described the studies of the space-time variability of two basic parameters of atomic and molecular physics: the fine-structure constant α and the Born–Oppenheimer parameter μ. The parameters α and μ remain the same on the scales of $\sim 10^{10}$ yr (in time) and $\sim 10^9$ parsec (in space) within the statistical accuracy of up-to-date experiments and observations (at the level of $\approx 0.015\%$). This means that electromagnetic and nuclear (quark-gluon) interactions have not changed on the Hubble space-time-scales. Thus the constancy of the fundamental constants, which holds despite the predictions of the theoretical models, remains one of the puzzles of the modern physics.

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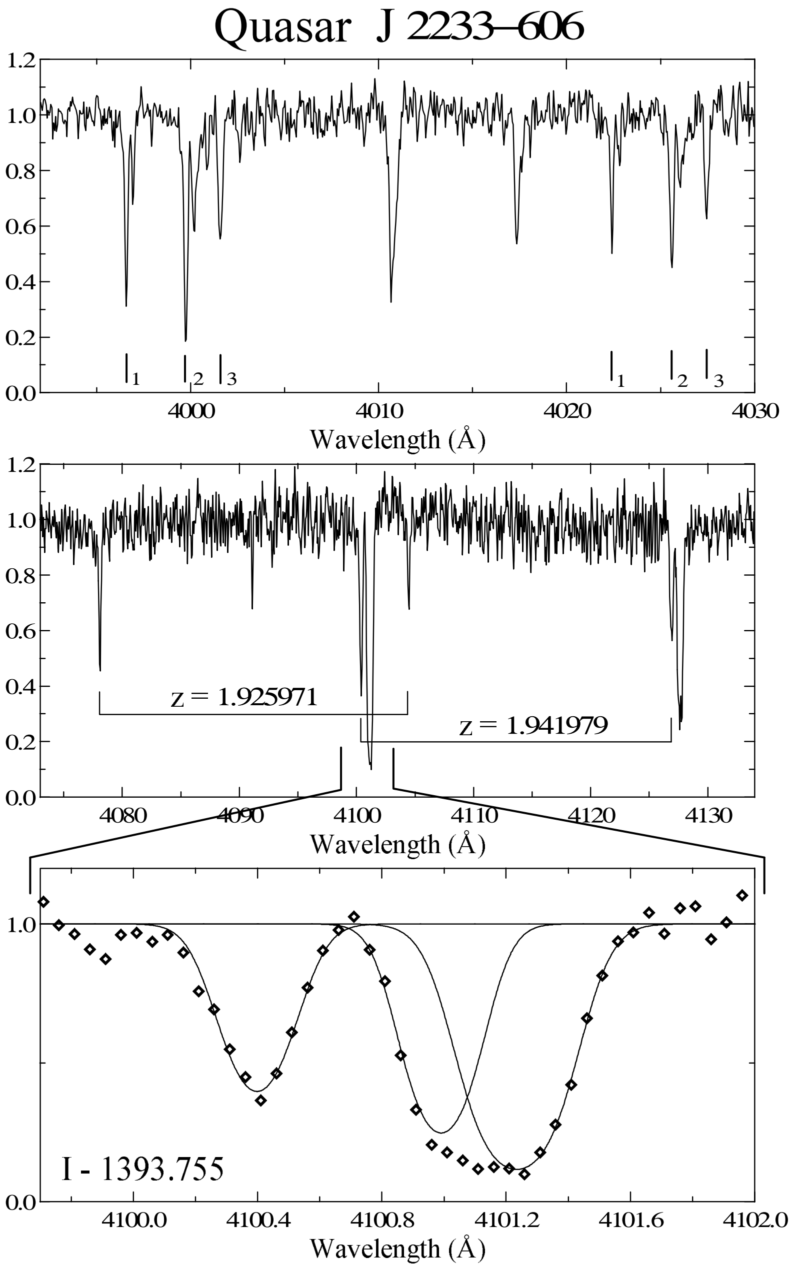

Figure 1: Section of the spectrum of quasar QSO J2233−66, obtained on the 3.9-meter Anglo-Australian Telescope (from Ref. [32]. A few Si IV doublets are marked, corresponding to different redshifts z. This figure illustrates the problem of blending: on the bottom panel, the short-wave component of the Si IV (λ = 1393.755Å) is shown, split in three components, one of which is clearly distinguished, whereas the remaining two overlap so strongly that the ambiguity in their decomposition renders them useless for the analysis under discussion.

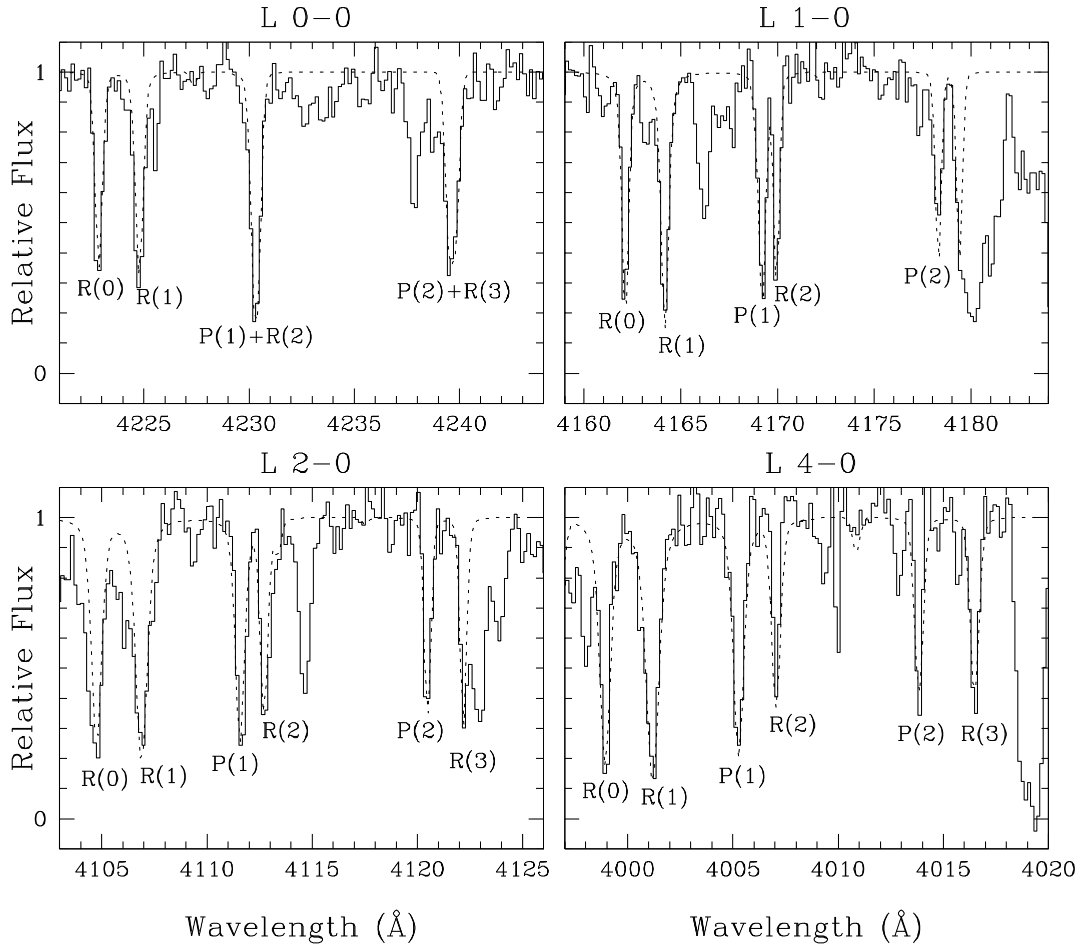

Figure 2: Selected parts of the spectrum of quasar PKS 0528−250 with absorption lines of H_2 molecules at the redshift $z = 2.81080$, obtained on the 4-meter Cerro-Tololo Inter-American Telescope (from Ref. [37]). Solid line – measured spectrum, dotted line – fit to the H_2 absorption component. The most distinct absorption lines of the Lyman band are labelled on the plot.