Studying possible variations of proton-to-electron mass ratio with microwave spectra of molecules [*]

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We discuss recent astrophysical results of the search for the variation of the proton-to-electron mass ratio μ based on the analysis of the microwave spectra of molecules. We argue that comparison of the apparent redshifts of the inversion lines of NH_3 and rotational molecular lines is extremely sensitive to μ-variation. High quality spectra from Perseus molecular cloud indicate μ-variation on the level $\delta\mu/\mu = -(3.5 \pm 1.4) \times 10^{-8}$.

1 Introduction

Recent discovery of the dark energy significantly increased the interest to the searches of the possible space-time variations of the fundamental constants. At present there is very strong limit on the present-time variation of the fine-structure constant $\alpha = e^2/\hbar c$ from laboratory experiments with Al^+ and Hg^+ optical clocks [1]:

$$\frac{\partial\alpha/\partial t}{\alpha} = (1.6 \pm 2.3) \times 10^{-17}\,\mathrm{yr}^{-1}. \tag{1}$$

Similar laboratory limit on the variation of the proton-to-electron mass ratio $\mu = m_p/m_e$ is significantly weaker. It was obtained in the experiment with SF_6 molecule [2]:

$$\frac{\partial\mu/\partial t}{\mu} = (-3.8 \pm 5.6) \times 10^{-14}\,\mathrm{yr}^{-1}. \tag{2}$$

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There are several proposals how to increase sensitivity of the laboratory experiments to the variation of μ (see review [3]), but it will probably take few years before these experiments are finished.

In addition to the laboratory experiments one can use astrophysical observations to study variation of fundamental constants μ and α at a much larger space and time scales. Reported in the literature optical data concerning the relative variation of these constants at redshifts $z \sim 1-3$ are controversial at the level of a few ppm (1 ppm $= 10^{-6}$). Such a spread probably indicates to the presence of some unaccounted systematics. We can state, however, that a conservative upper limit on the variability of these constants on the timescale of few billion years from optical observations is 10 ppm (see, for example, reviews [4, 3]). Since the hyperfine structure of optical lines is usually not resolved, observations in the optical range do not constrain time-variation of the nuclear gyromagnetic ratio g_n. Some of the limits on variation of all three constants, which follow from the observations at microwave and far infrared (FIR) ranges will be discussed below.

2 Sensitivity coefficients to the variation of fundamental constants

Astronomical estimates of the dimensionless physical constants are based on the comparison of the line centers in the spectral lines of astronomical objects and the corresponding laboratory values. In practice, in order to disentangle the line shifts caused by the motion of the object and by the putative effect of the variability of constants, lines with different sensitivities to the variation of fundamental constants should be used. The accuracy of the method depends on the linewidths and the respective sensitivity coefficients. If different elements are involved in the analysis, an additional source of errors due to the so-called Doppler noise arises. The Doppler noise is caused by non-identical spatial distributions of different species, which, in turn, causes different velocity distributions. It introduces offsets which can mimic or obliterate real signals. For this reason the lines of a single species are desired. If this is not possible, the lines with highest sensitivities should be used to suppress the systematic errors from the Doppler noise. As we will see below, this requirement is much easier met in microwave and FIR bands, than in optical and UV bands.

The observed linewidth Γ in extragalactic astrophysical spectra is determined by the Doppler broadening effect, i.e.

$$\frac{\Gamma}{\omega} = \frac{\Delta v}{c} \sim 10^{-5}\,, \tag{3}$$

where Δv is the velocity dispersion, c is the speed of light, and ω is the transition frequency. The typical values of Δv for extragalactic spectra are about $1-10$ km/s, which lead to the estimate (3). Obviously, the typical accuracy of the frequency measurements for a sufficiently strong single line does not depend on a waveband and is on the order of $\Delta\omega/\omega \sim 10^{-5}$. For the Galactic spectra Δv can be significantly smaller, on the order of 100 m s^{-1}, or less.

When we are studying variation of fundamental constants, we can increase accuracy by looking for lines with high sensitivity to the variation of fundamental constants. The dimensionless sensitivity coefficients are defined as:

$$\frac{\delta\omega}{\omega} = -\frac{z'-z}{1+z'} = K_\alpha \frac{\delta\alpha}{\alpha} + K_\mu \frac{\delta\mu}{\mu} + K_g \frac{\delta g_n}{g_n}\,, \tag{4}$$

where z' and z denote the apparent and actual redshifts respectively.

When we observe two lines with different sensitivities, their apparent redshifts will differ from each other if either of the fundamental constants has changed during the time passed:

$$\frac{\delta z'}{1+z'} = -\Delta K_\alpha \frac{\delta\alpha}{\alpha} - \Delta K_\mu \frac{\delta\mu}{\mu} - \Delta K_g \frac{\delta g_n}{g_n}\,. \tag{5}$$

Obviously, it is impossible to distinguish between variation of different constants from the observation of one pair of lines. Thus, we rewrite Eq. (5) in terms of the variation of a following combination of fundamental constants:

$$\frac{\delta z'}{1+z'} = -\frac{\delta F}{F}\,, \qquad F = \alpha^{\Delta K_\alpha} \mu^{\Delta K_\mu} g_n^{\Delta K_g}\,. \tag{6}$$

The summary of the sensitivity coefficients for different wavebands is presented in Table 1. These coefficients are calculated in the assumption, that atomic energy unit (27.2 eV) is independent of the fundamental constants. This assumption is only a matter of convenience, because, as one can see from Eq. (6), only the differences in sensitivities are important.

3 Limits on variation of constants from extragalactic microwave and FIR spectra

One of the most interesting and well studied extragalactic microwave spectra belongs to the object `B0218+357` at $z = 0.68$. This spectrum includes 21-cm Hydrogen line,

Table 1: Sensitivity coefficients for different wavebands

Transition	K_α	K_μ	K_g
Optical and UV bands			
typical E1-transition in atom	10^{-2} – 10^{-1}	10^{-3}	10^{-7}
electronic transitions in molecules	10^{-2}	10^{-2}	10^{-7}
Microwave and FIR bands			
fine-structure M1-transitions	2	0.0	0.0
vibrational transitions	0.0	-0.5	0.0
rotational transitions	0.0	-1.0	0.0
21-cm hyperfine transition in hydrogen	2.0	-1.0	1.0
18-cm Λ-doublet line in OH	-2	-3	10^{-1}
1.25-cm inversion line in NH_3	0.0	-4.5	0.0

several rotational lines of OH, HCO^+, and HCN molecules, 18-cm Λ-doublet lines of OH molecule, and several inversion lines of NH_3. These lines were used in [5, 6, 7] to place limits on different combinations of fundamental constants. According to Table 1 observations of the listed above lines for one object forms *complete* experiment, i.e. it allows to restrict variations of all three relevant fundamental constants:

$$\left\{\begin{array}{lcl} \delta\mu/\mu & = & (0.6 \pm 1.9)\times 10^{-6}\,, \\ \delta\alpha/\alpha & = & (0.9 \pm 6.4)\times 10^{-6}\,, \\ \delta g_n/g_n & = & (0 \pm 17)\times 10^{-6}\,. \end{array}\right. \tag{7}$$

These limits are placed at redshift $z = 0.68$, which corresponds to the look-back time of approximately 6.3 Gyr. In other words, if we (arbitrary) assume linear dependence of μ on time, the limit (7) on μ-variation translates into $\partial_t\mu/\mu = (1 \pm 3)\times 10^{-16}\,\mathrm{yr}^{-1}$. This limit is much stronger, than laboratory limit (2).

The fine-structure FIR lines of light ions are seen in emission for very distant objects with redshifts up to $z \sim 10$. In Ref. [8] the fine-structure 158 μm line of CII was compared to the rotational CO line for quasars `J1148+5251` and `BR 1202-0725` with respective redshifts $z = 6.42$ and $z = 4.69$. The absence of the meaningful difference in apparent redshifts allowed to place bounds on the variation of the parameter $F = \alpha^2\mu$:

$$\left\{\begin{array}{lcll} \delta F/F & = & (0.1 \pm 1.0)\times 10^{-4}\,, & z = 6.42\,, \\ \delta F/F & = & (1.4 \pm 1.5)\times 10^{-4}\,, & z = 4.69\,. \end{array}\right. \tag{8}$$

These limits are much weaker than (7). On the other hand, the redshift $z = 6.42$ corresponds to the look-back time of approximately 12.9 Gyr, or about 93% of the age of the Universe.

An intriguing result was recently obtained from the observations of ammonia inversion lines and rotational lines of CCS, HC_3N, and N_2H^+ from cold molecular clouds in the Milky Way [9]. Table 1 shows that combination of inversion and rotational lines is very sensitive to μ-variation. Analysis of the spectra from Perseus molecular cloud, Pipe nebulae, and infrared dark clouds (IRDCs) showed systematic positive offset $\Delta v = v_{\mathrm{rot}} - v_{NH_3}$ between ammonia inversion line and rotational lines on the order of $\Delta v \sim (30 \div 100)\,\mathrm{m\,s^{-1}}$. The most accurate spectra were observed for Perseus cloud [10], where $\Delta v = (36 \pm 15)\,\mathrm{m\,s^{-1}}$. If interpreted in terms of the μ-variation, this offset translates into the following non-zero variation [9]:

$$\delta\mu/\mu = -(3.5 \pm 1.4) \times 10^{-8}\,. \tag{9}$$

The look-back time for these clouds vary from 400 years for Pipe Nebulae to 800 years for Perseus and $\sim 10^4$ years for IRDCs. Such time-variation contradicts both laboratory and extragalactic limits, given by Eqs. (2) and (7). On the other hand, the estimate (9) is in agreement with predictions of some chameleon-type scalar-field models [11, 12]. Fundamental constants in these models depend on the local matter density. In the laboratory environment the latter is many orders of magnitude larger than in molecular clouds, which can explain result (9) and does not contradict limits (2) and (7) [matter density for the Galactic and extragalactic molecular clouds is similar].

The analysis of possible systematic velocity shifts on the level of tens of meters per second is very difficult and goes beyond these brief notes. A detailed discussion of the known sources of systematic effects in Ref. [9] has not reveled any explanation of the observed shifts. It is highly desirable to perform new dedicated observations of microwave spectra of Galactic molecular clouds to verify result (9).

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