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Spatial and temporal variations of fundamental constants

S. A. Levshakov[1], I. I. Agafonova[1], P. Molaro[2], and D. Reimers[3]

[1] Ioffe Physical-Technical Institute, St. Petersburg, Russia
e-mail: lev@astro.ioffe.rssi.ru
[2] INAF – Osservatorio Astronomico di Trieste, Trieste, Italy
[3] Hamburger Sternwarte, Hamburg, Germany

Abstract. Spatial and temporal variations in the electron-to-proton mass ratio, μ, and in the fine-structure constant, α, are predicted in non-Standard models aimed to explain the nature of dark energy. Among them the so-called chameleon-like scalar field models predict strong dependence of masses and coupling constants on the local matter density. To explore such models we estimated the parameters $\Delta\mu/\mu \equiv (\mu_{\rm obs} - \mu_{\rm lab})/\mu_{\rm lab}$ and $\Delta\alpha/\alpha \equiv (\alpha_{\rm obs} - \alpha_{\rm lab})/\alpha_{\rm lab}$ in two essentially different environments, – terrestrial (high density) and interstellar (low density), – from radio astronomical observations of cold prestellar molecular cores in the disk of the Milky Way. We found that $\Delta\mu/\mu = (22\pm4_{\rm stat}\pm3_{\rm sys})\times10^{-9}$, and $|\Delta\alpha/\alpha| < 1.1\times10^{-7}$. If only a conservative upper limit is considered, then $|\Delta\mu/\mu| \leq 3\times10^{-8}$. We also reviewed and re-analyzed the available data on the cosmological variation of α obtained from Fe I and Fe II systems in optical spectra of quasars. We show that statistically significant evidence for the changing α at the level of 10^{-6} has not been provided so far. The most stringent constraint on $|\Delta\alpha/\alpha| < 2\times10^{-6}$ was found from the Fe II system at $z = 1.15$ towards the bright quasar HE 0515–4414. The limit of 2×10^{-6} corresponds to the utmost accuracy which can be reached with available to date optical facilities.

Key words. Line: profiles – ISM: molecules – Radio lines: ISM – Techniques: radial velocities – quasars: absorption lines – Cosmology: observations

1. Introduction

Spatial and temporal variations in the electron-to-proton mass ratio, $\mu \equiv m_{\rm e}/m_{\rm p}$, and in the fine-structure constant, $\alpha \equiv e^2/(\hbar c)$, are not present in the Standard Model of particle physics but they arise quite naturally in grant unification theories, multidimensional theories and in general when a coupling of light scalar fields to baryonic matter is considered (Uzan 2003; Martins 2008; Chin *et al.* 2009). The light scalar fields are usually attributed to a negative pressure substance permeating the entire visible Universe and known as dark energy (Caldwell *et al.* 1998). This substance is thought to be responsible for a cosmic acceleration at low redshifts, $z < 1$ (Peebles & Rata 2003). However, scalar fields cause a problem since they could violate the equivalence principle which has never been detected in local tests (Turyshev *et al.* 2004). A plausible solution of this dissension was suggested with a so-called 'chameleon' model which assumes

Send offprint requests to: S. A. Levshakov that a light scalar field acquires an effective potential and an effective mass due to its coupling to matter that strongly depends on the ambient matter density (Khoury & Weltman 2004; Mota & Shaw 2007; Olive & Pospelov 2008). In such a way the scalar field may evade local tests of the equivalence principle since the range of the scalar-mediated force is too short ($\lambda_{\rm eff} \lesssim 1$ mm) to be revealed at the terrestrial matter densities. This is not the case, however, for the space based tests where the matter density is considerably lower, an effective mass of the scalar field is negligible, and an effective range for the scalar-mediated force is very large ($\lambda_{\rm eff} \gtrsim 1$ pc).

Calculations of atomic and molecular spectra show that different transitions have different sensitivities to changes in fundamental constants (Varshalovich & Levshakov 1993; Dzuba *et al.* 1999; Kozlov *et al.* 2008). Thus, measuring relative radial velocities, ΔV, between such transitions one can probe the hypothetical variation of physical constants. For instance, a spatial dependence of μ and α on the ambient matter density can be tested locally using terrestrial measurements of molecular transitions and comparing them with radio astronomical observations of molecular clouds in the disk of the Milky Way (here we have a typical difference between the environmental gas densities of ~19 orders of magnitude). Complementary to these measurements, a temporal dependence of μ and α on cosmic time can be tested through observations of high-redshift intervening absorbers seen in quasar spectra.

In this presentation we summarize our recent results on spatial and temporal variations of μ and α obtained at high redshifts $z > 0$ (QSO absorption systems) and at $z = 0$ (the Milky Way disk).

2. Cosmological tests ($z > 0$)

The cosmological variability of α can be probed by different methods. One of them, — the many-multiplet method, — was suggested by Dzuba *et al.* (1999) and extensively used in the analysis of quasar metal absorbers (Webb *et al.* 1999; Murphy *et al.* 2003; Chand *et al.* 2004). This method is based on the comparison of wavelengths of different transitions in different ions having different sensitivity coefficients to the variation of α and rising from the same QSO absorption-line system. However, the approach to estimate $\Delta\alpha/\alpha$ on base of different ions seems not to be very favorable: it requires many absorption systems in order to suppress kinematic effects caused by irregular velocity shifts between different ions, and its averaging procedure over many sight lines and over large range of redshifts may smear out a putative weak signal in $\Delta\alpha/\alpha$. It is clear that in order to obtain $\Delta\alpha/\alpha$ estimates at every particular redshift the kinematic effects must be suppressed. Such a procedure can be realized if lines of only one ion and arising from the same atomic levels are utilized (Levshakov 2004). The corresponding method, — the single ion differential α measurement (SIDAM), — and its applications to Fe I and Fe II systems are described below.

Fe I and Fe II are represented in optical spectra of quasars by several resonance transitions having different sensitivity coefficients. Under these conditions the accuracy of the $\Delta\alpha/\alpha$ estimates is limited by only two factors: (1) uncertainties in the calibration of the wavelength scale (see, e.g., Centurión *et al.*, these proceedings), and (2) unknown abundances of iron isotopes in a particular absorption system. For quasar spectra taken with the VLT, it is possible to reach the accuracy in the wavelength calibration of 30-50 m s^{-1} (Molaro *et al.* 2008a) which translates into the error in $\Delta\alpha/\alpha$ of $\sim 2\times10^{-6}$. The boundaries on isotopic composition of iron do not exceed 10^{-6} (Kozlov *et al.* 2004; Porsev *et al.* 2009). Thus, a single absorption system with iron ions can provide the accuracy of the $\Delta\alpha/\alpha$ estimate at the level of 10^{-6}.

2.1. Fe I at $z_{\rm abs}$ = 0.45

Many resonance transitions of neutral iron Fe I associated with the absorption-line system at $z_{\rm abs} = 0.45$ were identified in the spectrum of HE 0001–2340 by D'Odorico (2007). Among them there are Fe I lines with quite different sensitivity coefficients which makes such sys-

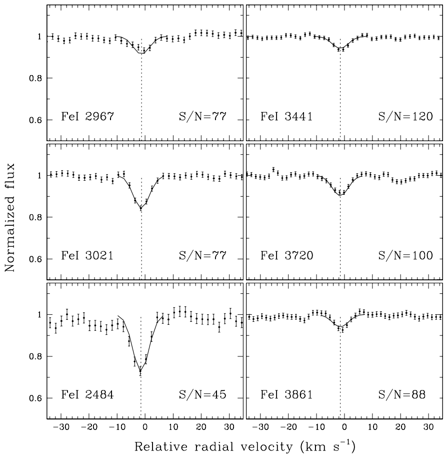

Fig. 1. Combined absorption-line spectra of Fe I associated with the $z_{\rm abs}$= 0.45 absorption-line system towards HE 0001–2340 (normalized intensities are shown by dots with 1σ error bars). The smooth curves show the model profiles. The normalized $\chi^2_\nu = 0.80$ ($\nu = 59$). The zero radial velocity is fixed at $z = 0.45207$.

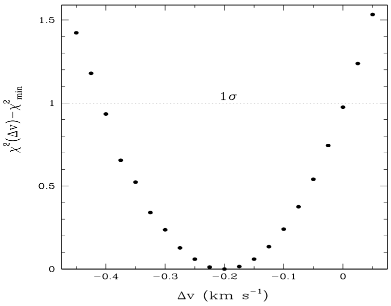

Fig. 2. χ^2 as a function of the velocity difference ΔV between the Fe I $\lambda\lambda$2967, 3021 Å lines and $\lambda\lambda$2484, 3441, 3720, 3861 Å lines for the one-component model shown in Fig. 1. The 1σ confidence level is determined by $\Delta\chi^2 = 1$ which gives $\sigma_{\Delta v} = 200$ m s^{-1}.

tems suitable for individual $\Delta\alpha/\alpha$ estimates. The sensitivity coefficients for Fe I transitions were calculated by Dzuba & Flambaum (2008) on our request and revealed to be highly sensitive to α change.

The profiles of the six selected Fe I lines are shown in Fig. 1. In this case a simple one-component model can describe adequately the observed intensities. The most probable value of $\Delta\alpha/\alpha = (7 \pm 7) \times 10^{-6}$ was calculated from the $\Delta\chi^2$-curve presented in Fig. 2. Here we combined the Fe I $\lambda\lambda$2967, 3021 Å lines having $Q \simeq 0.08$ and the Fe I $\lambda\lambda$2484, 3441, 3720, 3861 Å lines for which $Q \simeq 0.03$. In Fig. 2, the parameter ΔV is the velocity offset between these two groups of Fe I lines. In this case the estimate of $\Delta\alpha/\alpha$ is given by

$$\Delta\alpha/\alpha = \Delta V/(2c\Delta Q)\,, \quad (1)$$

where $\Delta V = V_1 - V_2$ is the difference between the radial velocities of these two groups of lines, and $\Delta Q = Q_2 - Q_1$.

We expect that with higher spectral resolution and higher S/N the accuracy of the $\Delta\alpha/\alpha$ estimate at $z_{\rm abs} = 0.45$ can be increased by several times since the Fe I lines in this system are extremely narrow (the Doppler width $\lesssim 1$ km s^{-1}) and have very simple profiles (D'Odorico 2007).

2.2. Fe II at $z_{\rm abs}$ = 1.84

The only QSO spectrum which was obtained especially with the objective to measure $\Delta\alpha/\alpha$ is the VLT/UVES spectrum of a bright quasar Q 1101–264 (Levshakov *et al.* 2007). This spectrum was observed with a high resolution (FWHM = 3.8 km s^{-1}) and S/N $\gtrsim$ 100. Analyzing the Fe II $\lambda\lambda$2600, 2382, and 1608 Å lines from the absorption system with $z_{\rm abs}$ = 1.84, we found $\Delta V = -180 \pm 85$ m s^{-1} between the Fe II λ1608 Å line which has negative sensitivity coefficient and the Fe II $\lambda\lambda$2600, 2382 Å transitions having almost identical positive sensitivity coefficients. In terms of $\Delta\alpha/\alpha$ this shift corresponds to $\Delta\alpha/\alpha = (5.4 \pm 2.5) \times 10^{-6}$.

When new sensitivity coefficients for the Fe II lines became available (Porsev *et al.* 2007), we repeated the analysis of this system including the unblended parts of the Fe II λ2374 Å line. The profile of this line is blended in the velocity range $-30 < V < -10$ km s^{-1} with telluric absorption and because of that it was not considered in Levshakov *et al.* (2007). This line has positive sensitivity coefficient like the Fe II $\lambda\lambda$2600, 2382 Å lines, but its oscillator strength is close to that of the weak line Fe II λ1608 Å. This allows us to control possible saturation effects in the strong

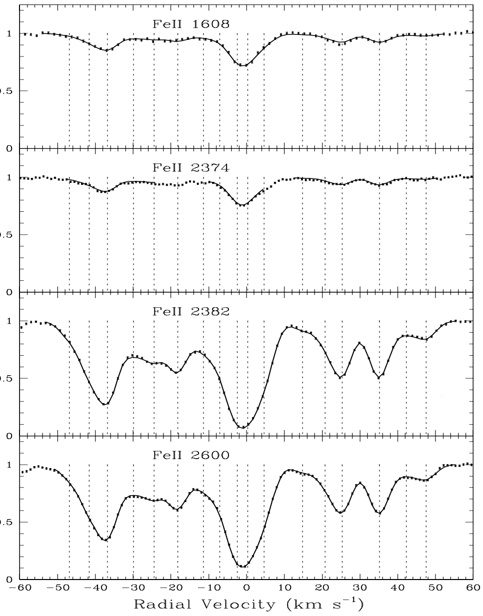

Fig. 3. Profiles of Fe II lines associated with the $z_{\rm abs}$= 1.84 damped Lyα system towards Q 1101–264 (normalized intensities are shown by dots with 1σ error bars). The S/N ratios per pixel (from the top panel to the bottom) are 100, 138, 120, 120. The smooth curves show the model profiles. Parts of the Fe II λ2374 Å line are contaminated in the ranges $-25 < V - 10$ km s^{-1} and $4 < V < 13$ km s^{-1} with telluric absorptions and not included in the analysis. The positions of the subcomponents of the equidispersion 17-component model are marked by the dotted vertical lines. The normalized χ^2_ν = 0.87 (ν = 300). The zero radial velocity is fixed at z = 1.838911.

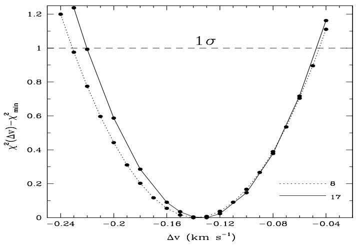

Fig. 4. χ^2 as a function of the velocity difference ΔV between the Fe II λ1608 Å and $\lambda\lambda$2374, 2382, 2600 Å lines (shown in Fig. 3) for the 8- and 17-component equidispersion models. The 1σ confidence level is determined by $\Delta\chi^2 = 1$ which gives $\sigma_{\Delta v}$ = 90 m s^{-1} for both represented models.

lines Fe II $\lambda\lambda$2600, 2382 Å caused by unresolved components which may lead to some radial velocity shifts between the apparent positions of the strong and weak Fe II lines. The profiles of all four Fe II lines (Fig. 3) were fitted by a series of mathematical models differing both in the number of components (from 8 to 17) and in the types of components: either all components have individual b-parameters or all components have identical b-parameters — the so-called equidispersion deconvolution (Levshakov *et al.* 1999).

The 1σ confidence limit for the velocity shift between the Fe II λ1608 Å and Fe II $\lambda\lambda$2600, 2383, 2374 Å lines was calculated via the $\Delta\chi^2$-curve (Fig. 4) and by means of Monte-Carlo simulations (Fig. 5). In turn, modeling of the data points in the Monte-Carlo simulations occurred also in two ways: (1) the method of bootstrapping residuals, and (2) the residuals were modeled by a Markov chain. The bootstrap procedure breaks correlations between the data points presented in the original QSO spectra (see, e.g., Appendix A in Levshakov *et al.* 2002), whereas the Markov chain approximation to the residuals allows us to save the original correlation in the simulated data. In all approaches the negative velocity shift between the Fe II λ1608 Å line and the Fe II $\lambda\lambda$2600, 2382, 2374 Å lines was stable reproduced with the most probable value of $\Delta V = -130 \pm 90$ m s^{-1} (as a 1σ limit the most conservative value from all trials is taken). In terms of $\Delta\alpha/\alpha$ this corresponds to $\Delta\alpha/\alpha$ = $(4.0 \pm 2.8) \times 10^{-6}$. We consider the result robust in this respect in disagreement with what claimed by Murphy *et al.* (2008) who have not provided a quantitative analysis of the z = 1.84 system to support their claim.

2.3. Fe II at $z_{\rm abs}$ = 1.15

The most accurate to date estimate of $\Delta\alpha/\alpha$ was obtained for the Fe II absorption system at $z_{\rm abs}$= 1.15 detected in the spectrum of one of the brightest high-redshift quasar HE 0515–4414 (Reimers *et al.* 1998). Quast *et al.*

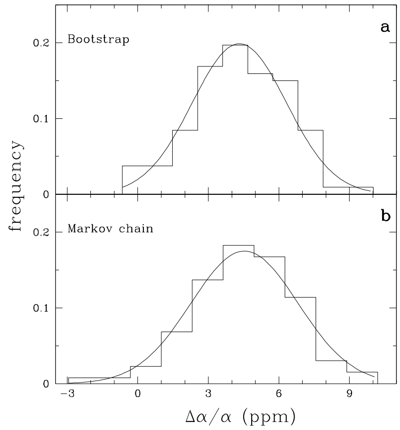

Fig. 5. Histograms of the simulated samples generated by the bootstrapping residuals (panel **a**) and by the Markov chain approximation (panel **b**) for the 17-component equidispersion model. The sample size $n = 100$ in both cases. The smooth curves are Gaussians defined by the first two moments of the corresponding samples: $(4.3 \pm 2.0) \times 10^{-6}$ (panel **a**), and $(4.5 \pm 2.3) \times 10^{-6}$ (panel **b**).

(2004) used co-added exposures taken with the VLT/UVES and reported $\Delta\alpha/\alpha = (-0.4 \pm 1.9) \times 10^{-6}$. Chand *et al.* (2006) re-observed this system with the high resolution and temperature stabilized spectrograph HARPS mounted on the ESO 3.6 m telescope at the La Silla observatory and obtained $\Delta\alpha/\alpha = (0.5 \pm 2.4) \times 10^{-6}$. We note that in both publications a wavelength calibration error was not taken into account, and once considered this their errors $\sigma_{\Delta\alpha/\alpha}$ would be a factor two larger.

Due to the brightness of HE 0515–4414, the S/N ratio in individual exposures of the VLT spectra is sufficiently high which allows us to process them separately, i.e. without co-adding. Levshakov *et al.* (2006) analyzed the best quality individual exposures and then averaged $\Delta\alpha/\alpha$ values produced from the pairs of Fe II lines (combinations of the blue line Fe II λ1608 Å and different red Fe II lines). The resulting mean value was $\Delta\alpha/\alpha = (-0.07 \pm 0.84) \times 10^{-6}$. However, it was overlooked that in this procedure the individual $\Delta\alpha/\alpha$ values from different pairs become correlated. Accounting for these correlations, as described in Molaro *et al.* (2008b), and using the updated sensitivity coefficients from Porsev *et al.* (2007) we correct the latter $\Delta\alpha/\alpha$ value to $\Delta\alpha/\alpha = (-0.12 \pm 1.79) \times 10^{-6}$. Thus, all $\Delta\alpha/\alpha$ estimates at $z_{\rm abs} = 1.15$, which are the most accurate so far, exclude any cosmological variations of α at the level of 2×10^{-6}.

3. Local tests ($z = 0$)

3.1. Estimate of $\Delta\mu/\mu$

Among numerous molecules observed in the interstellar medium, ammonia NH_3 is of a particular interest for the $\Delta\mu/\mu$ tests due to high sensitivity of the inversion frequency $(J, K) = (1, 1)$ at 23.7 GHz to a change in μ. Here $\Delta\mu/\mu \equiv (\mu_{\rm obs} - \mu_{\rm lab})/\mu_{\rm lab}$. The sensitivity coefficient ($Q = 4.5$) of the inversion transition was calculated by (Flambaum & Kozlov 2007):

$$(\Delta\nu/\nu)_{\rm inv} \equiv (\tilde{\nu} - \nu)/\nu = 4.5\,(\Delta\mu/\mu)\,, \quad (2)$$

where ν and $\tilde{\nu}$ are the frequencies corresponding to the laboratory value of μ and to an altered μ in a low-density environment, respectively. For the rotational frequencies we have $Q = 1$ and

$$(\Delta\nu/\nu)_{\rm rot} \equiv (\tilde{\nu} - \nu)/\nu = \Delta\mu/\mu\,. \quad (3)$$

Comparing the apparent radial velocities for the NH_3 inversion transition, $V_{\rm inv}$, with rotational transitions, $V_{\rm rot}$, of other molecules arising *co-spatially* with NH_3 one finds

$$\Delta\mu/\mu = 0.3(V_{\rm rot} - V_{\rm inv})/c \equiv 0.3\Delta V/c\,, \quad (4)$$

where c is the speed of light.

The parameter ΔV in (4) could be considered as the sum of two components, $\Delta V = \Delta V_\mu + \Delta V_n$, with ΔV_μ being the shift due to μ-variation, and ΔV_n is the so-called Doppler noise. The input of the Doppler noise to a putative $\Delta\mu/\mu$ signal can be reduced to some extent if the velocity shifts caused by inhomogeneous distribution of molecules and instrumental imperfections are minimized (for details, see Levshakov *et al.* 2009a).

To probe $\Delta\mu/\mu$ under different local environments, we analyzed at first high resolution spectra (FWHM = 25 m s^{-1}) of the NH_3 $(J, K) = (1, 1)$ and CCS $J_N = 2_1 - 1_0$ transitions obtained with the 100-m Green Bank

Telescope (GBT) by Rosolowsky *et al.* (2008) and Rathborne *et al.* (2008), and moderate resolution spectra (FWHM = 120 – 500 m s^{-1}) of the NH_3 $(J, K) = (1, 1)$, HC_3N $J = 5-4$, and N_2H^+ $J = 1-0$ transitions observed with the 45-m Nobeyama radio telescope by Sakai *et al.* (2008). These spectra showed a systematic velocity shift between rotational and inversion transitions with the most accurate value of $\Delta V = 52 \pm 7_{\rm stat} \pm 13_{\rm sys}$ m s^{-1} based on the NH_3 and CCS lines (Levshakov *et al.* 2008a).

Then we carried out our own observations of ammonia and other molecules with the 32-m Medicina, 100-m Effelsberg, and 45-m Nobeyama radio telescopes (Levshakov *et al.* 2009a).

Observations at the Medicina telescope were performed with both available digital spectrometers ARCOS (ARcetri COrrelation Spectrometer) and MSpec0 (high resolution digital spectrometer) which have channel separations of 4.88 kHz and 2 kHz, respectively. For ARCOS, this resolution corresponds to 62 m s^{-1} at the position of the ammonia inversion transition (23 GHz) and 80 m s^{-1} for the rotational HC_3N (2–1) line (18 GHz). For MSpec0, it is 25 m s^{-1} and 32 m s^{-1} at the corresponding frequencies.

The Effelsberg data were obtained with the HEMT (High Electron Mobility Transistor) dual channel receiver. The measurements were obtained in a frequency switching mode, with a frequency throw of ~5 MHz. The backend was an FFTS (Fast Fourier Transform Spectrometer), operated with its minimum bandwidth of 20 MHz and simultaneously providing 16384 channels for each polarization. The resulting channel widths are 15.4 and 20.1 m s^{-1} for NH_3 and HC_3N, respectively.

At Nobeyama we used a low-noise HEMT receiver, H22, for the NH_3 observations and the two sideband-separating SIS (Superconductor-Insulator-Superconductor) receiver, T100 (Nakajima *et al.* 2008), for the N_2H^+ observations. Both of them are dual polarization receivers. We observed two polarization simultaneously. Autocorrelators were employed as a backend with bandwidth and channel separation of 4 MHz and 4.375 kHz, respectively. This corresponds to the channel widths of 57 m s^{-1} at 23 GHz, and 14 m s^{-1} at 93 GHz.

The most accurate estimate in this case was based on the comparison of the radial velocities of the NH_3 inversion line with the rotational transition of HC_3N $J = 2-1$ observed with the 100-m Effelsberg telescope: $\Delta V = 23 \pm 4_{\rm stat} \pm 3_{\rm sys}$ m s^{-1}. The distribution of radial velocity offsets between the rotational and inversion transitions is shown in Fig. 6. The points represent molecular clouds with symmetric line profiles which can be described by a single-component Gaussian model. This requirement provides a better accuracy of the line center measurements. In the selected clouds the widths of the emission lines do not exceed greatly the Doppler width due to thermal motion of material (typical kinetic temperatures $T_{\rm kin} \sim 10$ K). This ensures that turbulent motion does not dominate in the line broadening and thus the selected molecular lines sample the same kinetic temperature and arise most likely *co-spatially*.

The difference between the GBT and Effelsberg ΔV values is probably connected to uncertainties in the laboratory frequencies. The most accurate frequencies for the ammonia inversion transitions are measured with the uncertainty $\varepsilon_\nu \lesssim 0.6$ m s^{-1} (Kukolich 1967; Hougen 1972). The HC_3N $J = 2-1$ laboratory frequencies are known with the error $\varepsilon_\nu \simeq 3$ m s^{-1} (Müller *et al.* 2005). The worst known is the frequency of the CCS $J_N = 2_1 - 1_0$ transition. The GBT radial velocities of CCS were measured with the frequency $\nu = 22344.033(1)$ MHz estimated by Yamamoto *et al.* (1990) from radio astronomical observations (1 kHz at 22.3 GHz corresponds to $\varepsilon_\nu = 13.4$ m s^{-1}). The only laboratory measurement available gives $\nu = 22344.029(4)$ MHz (Lovas *et al.* 1992). With this frequency we have $\Delta V = 6 \pm 7_{\rm stat} \pm 54_{\rm sys}$ m s^{-1}. The CDMS catalogue value $\nu = 22344.0308(10)$ MHz (Müller *et al.* 2005) yields $\Delta V = 22 \pm 7_{\rm stat} \pm 13_{\rm sys}$ m s^{-1} which is in line with the Effelsberg measurements based on the NH_3 and HC_3N lines.

These results show the importance of high precision laboratory measurements which are expected to provide radio frequencies with un-

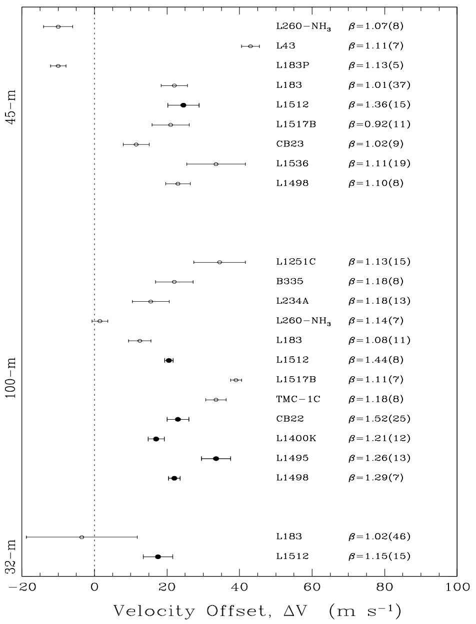

Fig. 6. Radial velocity offsets, ΔV, between the HC_3N $J = 2-1$ and NH_3 $(J, K) = (1, 1)$ transitions for the data obtained with the 32-m and 100-m telescopes, and between the N_2H^+ $J = 1-0$ and NH_3 $(J, K) = (1, 1)$ transitions for the 45-m telescope (1σ statistical errors are indicated). β is the ratio of the Doppler b-parameters: $\beta = b(NH_3)/b(HC_3N)$, or $\beta = b(NH_3)/b(N_2H^+)$. Given in parentheses are 1σ errors. The filled circles mark sources with thermally dominated motions.

certainties $\sim$1 m s^{-1} to be consistent with contemporary radio astronomical observations.

If we interpret the most accurate to date Effelsberg measurements of ΔV in terms of the electron-to-proton mass ratio variation, then $\Delta\mu/\mu = (22 \pm 4_{\rm stat} \pm 3_{\rm sys}) \times 10^{-9}$.

3.2. Constraint on $\Delta\alpha/\alpha$

Complementary to the $\Delta\mu/\mu$ estimate, constraints on α-variation can be obtained from the comparison of the atomic fine-structure (FS) and molecular rotational transitions (Kozlov *et al.* 2008; Levshakov *et al.* 2008b). In this case the velocity difference between the rotational and FS lines is sensitive to the combination of α and μ, $F = \alpha^2/\mu$:

$$\Delta F/F \equiv 2\Delta\alpha/\alpha - \Delta\mu/\mu = \Delta V/c\,, \qquad (5)$$

where $\Delta V = V_{\rm rot} - V_{\rm fs}$.

For practical applications we may compare the FS transitions of carbon [C I] with rotational transitions of ^{13}CO. The spatial distribution of ^{13}CO is closely traced by the [C I] FS lines (Spaans & van Dishoeck 1997; Ikeda *et al.* 2002; Papadopoulos *et al.* 2004). The rest hyper-fine frequencies of low-J rotational transitions of ^{13}CO are known with very high accuracy, $|\varepsilon_v| \lesssim 0.1$ m s^{-1} (Cazzoli *et al.* 2004). The most precise rest frequencies to date for the [C I] $J = 1-0$ transition 492160.651(55) MHz (Yamamoto & Saito 1991) and $J = 2-1$ transition 809341.97(5) MHz (Klein *et al.* 1998) restrict the uncertainties of the line centers to $\varepsilon_v = 33.5$ m s^{-1} and 18.5 m s^{-1}, respectively. Thus, if we take $\varepsilon_v \simeq 34$ m s^{-1} as the most conservative error of the line centering in a pair of ^{13}CO–[C I] lines, then the limiting accuracy for $\Delta F/F$ is about 0.1 ppm.

The analysis of the published results on [C I] and ^{13}CO low resolution observations (FWHM = 0.2 − 1.0 km s^{-1}) of cold molecular cores gives $\Delta V = 0 \pm 60_{\rm stat} \pm 34_{\rm sys}$ m s^{-1} (Levshakov *et al.* 2009b), which leads to a limit $|\Delta F/F| < 2.3 \times 10^{-7}$. With the obtained estimate of $\Delta\mu/\mu$, one finds from (5) that $|\Delta\alpha/\alpha| < 1.1 \times 10^{-7}$.

This result is already an order of magnitude more sensitive than the bound on the cosmological α-variation found from absorption systems of quasars. The present estimate of $\Delta\alpha/\alpha$ at $z = 0$ can be considerably improved if higher resolution spectra of molecular cores will be obtained and the rest frequencies of the [C I] FS transitions will be measured with better accuracy.

4. Conclusions

Our current results of astrophysical tests on spatial and temporal variations of fundamental constants can be summarized as follows.

1. The relative radial velocities of the rotational transitions in HC_3N ($J = 2-1$)

and the inversion transition in NH_3 $(J, K) = (1, 1)$ measured with the 100-m Effelsberg radio telescope reveal a velocity offset of $\Delta V = 23 \pm 4_{stat} \pm 3_{sys}$ m s^{-1}. This offset is regularly reproduced in observations of different cold molecular cores with different facilities at the 32-m Medicina and 45-m Nobeyama radio telescopes.

2. Being interpreted in terms of the electron-to-proton mass ratio variation, the found velocity offset corresponds to $\Delta\mu/\mu = (22 \pm 4_{stat} \pm 3_{sys}) \times 10^{-9}$. To cope with negative results obtained in laboratory experiments, a chameleon-like scalar field is required to explain the non-zero $\Delta\mu$ value.
3. A new approach to probe α-variations using the fine-structure transitions in atomic carbon [C I] and low-J rotational transitions in ^{13}CO is suggested, and a strong constraint on the dependence of α on the ambient matter density is deduced at $z = 0$: $|\Delta\alpha/\alpha| < 1.1 \times 10^{-7}$.
4. Another method to measure the cosmological variability of α from resonance transitions of neutral iron Fe I is discussed and applied to the Fe I system at $z_{abs} = 0.45$. The resulting constraint is $\Delta\alpha/\alpha = (7\pm7)\times10^{-6}$.
5. The Fe II system at $z_{abs} = 1.84$ is re-analyzed and a corrected value of $\Delta\alpha/\alpha$ is obtained: $\Delta\alpha/\alpha = (4.0 \pm 2.8) \times 10^{-6}$.
6. For the Fe II system at $z_{abs} = 1.15$ the overlooked correlations between individual $\Delta\alpha/\alpha$ values are now taken into account that gives $\Delta\alpha/\alpha = (-0.12 \pm 1.79) \times 10^{-6}$.
7. It is shown that spectral radio observations in the Milky Way are at present the most sensitive tool to probe the values of fundamental constants at different ambient physical conditions. The internal (statistical) error of our Effelsberg data is $\sigma_{\Delta\mu/\mu} = 4 \times 10^{-9}$ which is about 1000 times lower as compared with the error in optical observations of quasars.
8. Since extragalactic molecular clouds have gas densities similar to those in the interstellar medium, the value of $\Delta\mu/\mu$ in high-z molecular systems is expected to be at the same level as in the Milky Way, i.e. $\Delta\mu/\mu \sim 10^{-8}$ — providing no temporal dependence of the electron-to-proton mass ratio is present.

To conclude, we note that in order to be completely confident that the revealed velocity shift between rotational and inversion lines is not due to kinematic effects in the molecular clouds but reflects a density-modulated variation of $\Delta\mu/\mu$, new high precision radio-astronomical observations are needed for a wider range of objects. Besides, such observations should include essentially different molecules with tunneling transitions sensitive to the changes in μ and molecules with Λ-doublet lines which also exhibit enhanced sensitivity to variations of μ and α (Kozlov 2009). It is also very important to measure the rest frequencies of molecular transitions with an accuracy of about 1 m s^{-1} in laboratory experiments — in some cases the present uncertainties in the rest frequencies are larger than the errors of radio-astronomical measurements. In addition, search for variations of the fine-structure constant α in the Milky Way disk using mid- and far-infrared fine-structure transitions in atoms and ions, or search for variations of the combination of α^2/μ using the [C II] and/or [C I] fine-structure transitions and low-lying rotational lines of CO would be of great importance for cross-checking the results.

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