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Limits on the space-time variations of fundamental constants

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Abstract. We report on new tests that improve our previous (2009-2010) estimates of the electron-to-proton mass ratio variation, $\mu = m_e/m_p$. Subsequent observations (2011-2013) at the Effelsberg 100-m telescope of a sample of eight molecular cores from the Milky Way disk reveal systematic errors in the measured radial velocities varying with an amplitude $\approx \pm 0.01$ km s^{-1} during the exposure time. The averaged offset between the radial velocities of the rotational transitions of HC_3N(2-1), HC_5N(9-8), HC_7N(16-15), HC_7N(21-20), and HC_7N(23-22), and the inversion transition of NH_3(1,1) gives $\langle \Delta V \rangle = 0.002 \pm 0.015$ km s^{-1} [3σ confidence level (C.L.)]. This value, when interpreted in terms of $\Delta\mu/\mu = (\mu_{\rm obs} - \mu_{\rm lab})/\mu_{\rm lab}$, constraints the μ-variation at the level of $\Delta\mu/\mu < 2 \times 10^{-8}$ (3σ C.L.), which is the most stringent limit on the fractional changes in μ based on radio astronomical observations.

Key words. Line: profiles – ISM: molecules – Radio lines: ISM – Techniques: radial velocities – elementary particles

1. Introduction

This study is aimed to test whether dimensionless physical constants are really constants, or whether they vary with space and time. The latter would imply, at some level, a violation of the Einstein equivalence principle (EEP), i.e., local position invariance (LPI) and local Lorentz invariance (LLI), as suggested in a number of unification theories (for reviews, see Uzan 2011; Liberati 2013). In particular, LPI postulates that the outcome of any local nongravitational experiment is independent of where and when it is performed, i.e., that the fundamental physical laws are space-time invariant. Experimental validation of EEP is one of the most important topics of modern physics allowing us to probe the applicability limits of the Standard Model (SM) of particle physics.

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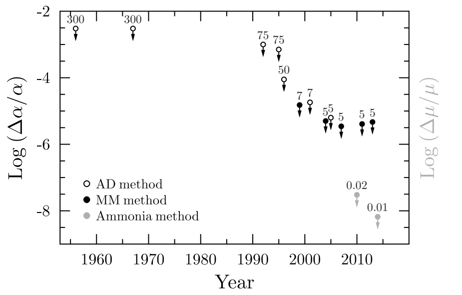

Fig. 1. Astronomical constraints on α- and μ-variations (1σ C.L.) for the period from 1956 to 2013. Above each point, the spectral resolution (FWHM in km s^{-1}) is indicated. α-variation constraints are based on the alkali-doublet (AD) and many-multiplet (MM) methods, whereas μ-variation – on the ammonia method. The data points for the AD method are taken from Savedoff (1956), Bahcall et al. (1967), Levshakov (1992), Varshalovich & Potekhin (1995), Varshalovich et al. (1996), Murphy et al. (2001), Chand et al. (2005); MM method – Webb et al. (1999), Quast et al. (2004), Srianand et al. (2007), Agafonova et al. (2011), Molaro et al. (2013); ammonia method – from Levshakov et al. (2010a), Levshakov et al. (2013a). The figure shows that limits on the α- and μ-variations just follow the spectral resolution approximately as $\Delta\alpha/\alpha$ (or $\Delta\mu/\mu$) $\propto$ $1/10th$ of the pixel size.

At the same time, precision limits delivered from such experiments serve as restrictions for the numerous new theories beyond the SM and can help to distinguish between them.

Figure 1 demonstrates how upper limits on variations of physical constants obtained from astronomical spectra just followed the available spectral resolution. Up to now, no signals have yet been detected in the range of fractional changes from $\sim 3 \times 10^{-2}$ to $\sim 3 \times 10^{-8}$. Thus, any progress in improving the existing limits can be achieved from observations of narrow spectral lines involving higher spectral resolutions to resolve completely their profiles. At the moment, the resolution of radio telescopes exceeds that of optical facilities by order(s) of magnitude; an additional and very attractive property of microwave radio observations is that some molecular transitions from this frequency range are extremely sensitive to the putative variations of the fundamental physical constants (see a review by Kozlov & Levshakov 2013).

Flambaum & Kozlov proposed in 2007 the so-called ammonia method to test the variability of the electron-to-proton mass ratio, μ. Using this method for a sample of cold molecular cores from the Milky Way disk we obtained the following estimate on the spacial μ-variations (Levshakov et al. 2010a, 2010b): $\Delta\mu/\mu = (26 \pm 1_{\rm stat} \pm 3_{\rm sys}) \times 10^{-9}$ (1σ C.L.). However, further studies revealed significant instrumental instabilities in the measurements of line radial velocities which were not accounted for in the above value. Thus, we performed a new set of observations of the same targets and with the same instrument (100-m Effelsberg radio telescope) in order to get an insight into this previously unknown systematics. Here we present the recent results.

2. Observations

Observations in 2011-2013 targeted a sample of nine cold ($T_{\rm kin}$ $\sim$ 10K) and dense ($n_{\rm H_2}$ $\sim$ 10^4 cm^{-3}) starless molecular cores located in the Milky Way disk. The selected clouds are known to have narrow molecular emission lines (full width at half maximum, FWHM < 1 km s^{-1}) what makes them the most suitable targets to precise measurements of relative radial velocities (RV). The following molecular transitions were observed: NH_3(1,1) 23.7 GH, HC_3N(2-1) 18.2 GHz, HC_5N(9-8) 23.9 GHz, HC_7N(16-15) 18.0 GHz, HC_7N(21-20) 23.7 GHz, and HC_7N(23-22) 25.9 GHz.

The source coordinates are taken from Levshakov et al. (2010b, 2013b). Observations used the Effelsberg 100-m radio telescope as described in Levshakov et al. (2010a, 2013b).

In 2011, the measurements were obtained in frequency switching (FSW) mode using a frequency throw of ±2.5 MHz. The backend was a fast Fourier transform spectrometer (FFTS), operated with a bandwidth of 20 MHz, which simultaneously provided 16 384 channels for each polarization. The resulting channel width was 0.015 km s^{-1}. However, the true velocity resolution is about 1.6 times coarser.

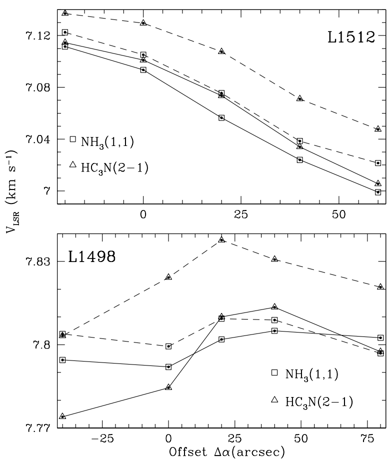

Fig. 2. The line-of-sight velocities ($V_{\rm LSR}$) of NH_3 $(J, K) = (1, 1)$ (squares) and HC_3N $J = 2 - 1$ (triangles) transitions at different radial distances along the main diagonal cuts towards the molecular cores L1512 and L1498 measured in 2010 (dashed lines) and in 2011 (solid lines) at the Effelsberg 100-m radio telescope. The half-power beam width at 23 GHz is 40″, the backend is the fast Fourier transform spectrometer (FFTS) with the channel separation $\delta v = 0.015$ km s^{-1}.

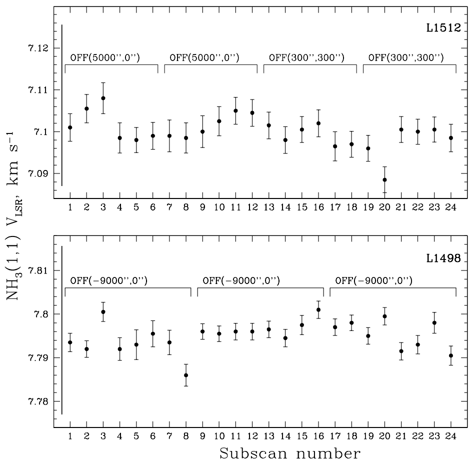

Fig. 3. The line-of-sight velocities ($V_{\rm LSR}$) of the NH_3(1,1) transition (dots with 1σ error bars) towards the ammonia peaks in the molecular cores L1512 and L1498 measured continuously in the position switching mode (PSW) at the Effelsberg 100-m radio telescope in April, 2012. The exposure time at each point is 150 sec. The PSW offsets are shown in parentheses. The backend was an extended fast Fourier transform spectrometer (XFFTS) with a channel separation $\delta v = 0.039$ km s^{-1} (marked by vertical lines). The instability of the $V_{\rm LSR}$ measurements of an amplitude $\approx \pm 0.01$ km s^{-1} (i.e., $\approx 1/4th$ of the channel width) is revealed.

In 2012-2013, we performed the measurements in the position switching (PSW) mode with the backend XFFTS (eXtended bandwidth FFTS) operating with 100 MHz bandwidth and providing 32 768 channels for each polarization. The resulting channel width was 0.039 km s^{-1}, but the true velocity resolution is 1.16 times coarser (Klein et al. 2012).

3. Results

To check the reproducibility of the relative RVs of the NH_3(1,1) and HC_3N(2-1) lines we re-observed two molecular cores L1512 and L1498 in 2011. The procedure was the same as in 2010 observations: cores were mapped at the same offsets and in the same lines. Namely in the (1,1) inversion transition of NH_3 complemented by rotational lines of other molecular species. The comparison of radial velocities of NH_3 inversion lines, $V_{\rm inv}$, with radial velocities of rotational transitions, $V_{\rm rot}$, provides a sensitive limit to the variation of μ (Flambaum & Kozlov 2007):

$$\Delta\mu/\mu = 0.289(V_{\rm rot} - V_{\rm inv})/c \approx 0.3\Delta V/c\,, \quad (1)$$

where c is the speed of light.

The measured RVs (Levshakov et al. 2010a) at different radial distances along the main diagonal cuts towards L1512 and L1498 are shown in Fig. 2. It is seen that the velocity offsets ΔV exhibit quite different behavior between 2010 and 2011, what is probably an effect of unknown systematic errors.

To figure out the source of these errors, we performed in 2012 a set of continuous observations of L1512 and L1498 targeting their ammonia peaks. Observing in PSW mode, we also used different OFF positions to check possible contamination from an extended background ammonia emission (which was not detected).

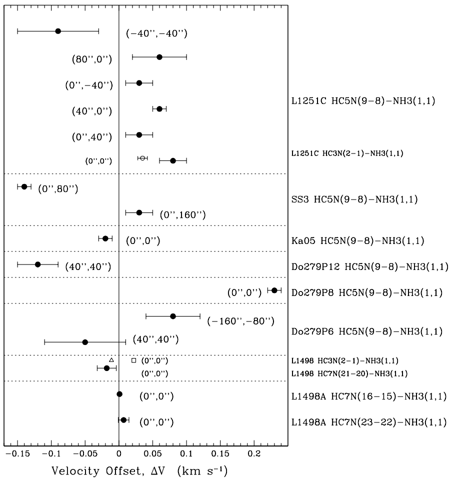

Fig. 4. Radial velocity differences, ΔV, between rotational transitions of different molecules and the $NH_3(1,1)$ line for the sources observed at the Effelsberg 100-m telescope (2011-2013). 1σ statistical errors are indicated. In the panel, given in parentheses are the coordinate offsets in arcsec. Filled circles – data from Levshakov et al. (2013a); open triangle – this paper; open circle and square – Levshakov et al. (2010a, 2010b);

The resulting time series are shown in Fig. 3. The RV values fluctuate with an amplitude of $\approx \pm 0.01$ km s^{-1}, i.e., $\approx 1/4th$ of the channel width.

To check whether the sky frequency is identical with the frequency coming out of the backend we carried out a test with an artificial signal at 22000.78125 MHz. The synthesizer frequency was accurate to about 1 Hz, and the frequency scale was found to be accurate to about 32 Hz (≈ 0.0004 km s^{-1}).

In our observations, the sky frequencies were reset at the onset of each subscan. Therefore, the longer a subscan the higher the error caused by Doppler shifts during the exposure time (e.g., for a 5 min scan, it is about 0.004 km s^{-1} at Effelsberg latitude). We corrected some of our observations to account for residual Doppler shifts. This didn't show a significant change in the results, however.

Another source of errors which can affect the $\Delta\mu/\mu$ estimates with the ammonia method is the possible segregation of molecules in molecular cores. Figure 4 shows our measurements in 2013 (filled circles) of the relative RVs between $NH_3(1,1)$ and other molecules towards eight molecular cores (L1498A is a gas condensation in L1498, see Fig. 3 in Kuiper et al. 1996) at different offsets. Previous values, obtained in 2009-2011, are marked by open symbols. A spread of the velocity offsets ΔV is clearly seen.

Thus, we conclude that noise in the ΔV values consists of at least two components: one is due to chemical differentiation and velocity gradients within the molecular cores, possibly being amplified by small variations in the telescope pointing. Additionally, some scatter in the RVs may be caused by the different optical depths of the hyperfine structure transitions. However, all these effects may be random from one observation to another, and, being averaged over a sample of targets, should be reduced to some extent. Applied to our sample of $n = 18$ independent ΔV offsets shown in Fig. 4, this gives the weighted mean $\langle \Delta V \rangle = 0.002 \pm 0.015$ km s^{-1} (3σ C.L.). Being interpreted in terms of $\Delta\mu/\mu = (\mu_{\rm obs} - \mu_{\rm lab})/\mu_{\rm lab}$, this value of $\langle \Delta V \rangle$ constraints the μ-variation at the level of $\Delta\mu/\mu < 2 \times 10^{-8}$ (3σ C.L.), which is the most stringent limit on the spatial variation of μ based on radio astronomical observations. The same order of magnitude upper limit on $\Delta\mu/\mu$ was obtained from independent observations of L1512 and L1498 at the Medicina 30-m telescope (Levshakov et al. 2013a).

We note in passing that mapping of the dense molecular cores in different molecular lines shows that there is, in general, a good correlation between NH_3, N_2H^+, and HC_3N distributions (Fuller & Myers 1993; Hotzel et al. 2004; Tafalla et al. 2004; Pagani et al. 2009). However, in some clouds NH_3 is not traced by HC_3N, as, e.g., in the dark cloud TMC-1, where peaks of line emission are offset by $7'$ (Olano et al. 1988). In our case, we observe systematic velocity shifts between NH_3 and other species. This can be expected since C-bearing molecules are usually distributed in the outer parts of the cores, whereas N-bearing molecules trace the inner parts.

4. Discussion

The obtained local constraint on the spatial μ-variation, $\Delta\mu/\mu < 2 \times 10^{-8}$ (3σ C.L.), can be used to set limits on changes in α. This, however, is strongly model dependent. For example, within the grand unification model (GUT) a variation of α would imply considerably larger fractional changes in the mass scale of the strong force in QCD, $\Lambda_{\rm QCD}$, and in quark and electron masses leading to

$$\Delta\mu/\mu \propto R\Delta\alpha/\alpha\,, \tag{2}$$

where $R \sim 40$ (e.g., Langacker et al. 2002; Flambaum et al. 2004). This gives a limit on $|\Delta\alpha/\alpha| < 10^{-10}$ (1σ C.L.). The value of R is, however, poorly constrained. Depending on the theory, it varies from −235 to +46 (examples are given in Section 5.3.1 in Uzan 2011). The only way to distinguish between theories is to measure $\Delta\alpha/\alpha$ and $\Delta\mu/\mu$ independently.

At higher redshifts, the most stringent limit on cosmological μ-variation was set at $z = 0.89$, $|\Delta\mu/\mu| < 10^{-7}$ (Bagdonaite et al. 2013). This would imply that $|\Delta\alpha/\alpha| < 2.5\times10^{-9}$ (1σ C.L.) at epoch 7×10^9 yr, which means in turn that $|\dot{\alpha}/\alpha| < 4 \times 10^{-19}$ yr^{-1}. At very high redshift, $z = 5.2$ (epoch 12.9 Gyr), the current limit is $|\Delta\alpha/\alpha| < 8 \times 10^{-6}$ (1σ C.L.) corresponding to $|\dot{\alpha}/\alpha| < 6\times10^{-16}$ yr^{-1} (Levshakov et al. 2012). We note that most stringent limits set by the Oklo fossil reactor and by terrestrial atomic clock experiments are, respectively, $|\dot{\alpha}/\alpha| < 5 \times 10^{-17}$ yr^{-1} (Uzan 2011), and $|\dot{\alpha}/\alpha| < 4 \times 10^{-17}$ yr^{-1} (Rosenband et al. 2008). Thus, despite many efforts, the space-time variations in μ and α have never been detected either in laboratory or astronomical experiments.

It only remains to hope that significant improvements in radio astronomical observations will allow us to probe variations of μ at levels of $\Delta\mu/\mu \sim 10^{-9} - 10^{-10}$, leading to even more stringent results and eventually to the detection of a real variation.

5. Conclusions

We have used the Effelsberg 100-m telescope to observe the NH_3(1,1) 23.7 GHz, HC_3N(2-1) 18.2 GHz, HC_5N(9-8) 23.9 GHz, HC_7N(16-15) 18.0 GHz, HC_7N(21-20) 23.7 GHz, and HC_7N(23-22) 25.9 GHz spectral lines in high-density molecular cores devoid of associated IR sources. The results obtained are as follow.

1. In order to test the reproducibility of the measurements of the relative radial velocities between the NH_3(1,1) and HC_3N(2-1) transitions observed towards dark molecular cores in 2009-2010 at the Effelsberg 100-m telescope, we re-observed two clouds L1512 and L1498 and revealed discrepancy between the $V_{lsr}(HC_3N) - V_{lsr}(NH_3)$ values which is as high as the channel width, $\Delta V \lesssim 0.02$ km s^{-1}.
2. Continuous observations of L1512 and L1498 in 2012 at a fixed position towards the ammonia peaks showed that the measured radial velocity $V_{lsr}(NH_3)$ fluctuates during the exposure time of 2 hours with an amplitude $\approx \pm0.01$ km s^{-1}, i.e., with approximately $1/4th$ of the channel width.
3. Tests with the synthesizer frequency at 2000.78125 MHz showed that the sky frequency is accurate to about 32 Hz, i.e., ≈ 0.0004 km s^{-1}.
4. Taking into account the revealed errors and averaging relative velocities over a sample of eight molecular cores ($n = 18$ independent ΔV values) observed in 2013, we find a null offset $\langle\Delta V\rangle = 0.002 \pm 0.015$ km s^{-1} (3σ C.L.) between the rotational and inversion transitions of the above mentioned molecules.
5. If this offset is interpreted in terms of $\Delta\mu/\mu = (\mu_{\rm obs} - \mu_{\rm lab})/\mu_{\rm lab}$, then the spatial μ-variation is constrained at the level of $\Delta\mu/\mu < 2 \times 10^{-8}$ (3σ C.L.), that is the strictest limit for the validity of the LPI principle based on radio astronomical observations.

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