Testing the Variation of Fundamental Constants by Astrophysical Methods: Overview and Prospects

S.A. Levshakov[1,2]

E-mail: *lev@astro.ioffe.rssi.ru*

By measuring the fundamental constants in astrophysical objects one can test basic physical principles as space-time invariance of physical laws along with probing the applicability limits of the standard model of particle physics. The latest constraints on the fine structure constant α and the electron-to-proton mass ratio μ obtained from observations at high redshifts and in the Milky Way disk are reviewed. In optical range, the most accurate measurements have already reached the sensitivity limit of available instruments, and further improvements will be possible only with next generation of telescopes and receivers. New methods of the wavelength calibration should be realized to control systematic errors at the sub-pixel level. In radio sector, the main tasks are the search for galactic and extragalactic objects suitable for precise molecular spectroscopy as well as high resolution laboratory measurements of molecular lines to provide accurate frequency standards. The expected progress in the optical and radio astrophysical observations is quantified.

1 Introduction

The idea that the fundamental physical constants may vary on the cosmological time scale has been discussing since 1937, when Milne and Dirac argued about possible variations of the Newton constant G during the lifetime of the universe [1, 2]. Currently, the subject of the cosmological variation of fundamental constants is closely related to emergence considerations of different cosmological models inspired by the discovery of late time acceleration of the expansion of the universe [3, 4]. The possibility that dimensionless coupling constants such as electron-to-proton mass ratio $\mu = m_{\rm e}/m_{\rm p}$ and the fine structure constant $\alpha = e^2/\hbar c$ may roll with cosmic time has recently been reviewed in [5, 6, 7, 8].

The variation of fundamental constants would imply a violation of the Einstein equivalence principle (EEP), that is, local position invariance (LPI) and local Lorentz invariance (LLI). In particular, a changing α accompanied by variation in other coupling constants can be associated with a violation of LLI [9], and LPI postulates that the fundamental physical laws are space-time invariant.

[1] A.F. Ioffe Physical-Technical Institute, St. Petersburg, Russia

[2] St. Petersburg Electrotechnical University "LETI", Russia

V. Grinin et al. (eds) Radiation mechanisms of astrophysical objects. Yerevan: Edit Print, 2017, pp. 323–330.

The standard model of particle physics (SM) is based on the EEP; thus, we can probe the applicability limits of the SM and new types of interactions by experimental validation of the EEP.

In spite of some claims that changes in α or μ were marginally detected at high redshifts, to date no confirmed variation of dimensionless coupling constants has been found on astronomical space-time scales. Below we review current observational constraints on α and μ variations which provide limits on the allowed deviations from the SM and ΛCDM cosmology.

2 Basics of the astronomical measurements

Two dimensionless coupling constants μ and α are of particular interest for astronomical studies since their fractional changes $\Delta\mu/\mu = (\mu_{\rm obs} - \mu_{\rm lab})/\mu_{\rm lab}$, and $\Delta\alpha/\alpha = (\alpha_{\rm obs} - \alpha_{\rm lab})/\alpha_{\rm lab}$ can be accurately measured from spectral line profiles of Galactic and extragalactic sources.

Differential measurements of $\Delta\mu/\mu$ and $\Delta\alpha/\alpha$ are based on the comparison of the line centers in the absorption/emission spectra of cosmic objects and the corresponding laboratory values. It was shown that electro-vibro-rotational lines of H_2 [10] and CO [11] have their own sensitivities to μ-variation. Similarly, each atomic transition is characterized by its individual sensitivity to α-variation [12]. The dependence of an atomic frequency ω on α in the comoving reference frame of a distant object located at redshift z is given by $\omega_z = \omega + qx + O(x^2)$, where $x \equiv (\alpha_z/\alpha)^2 - 1$. Here ω and ω_z are the frequencies corresponding to the present-day value of α and that at a redshift z. The so-called q factor is an individual parameter for each atomic transition [12]. If $\alpha_z \neq \alpha$, then $x \neq 0$ and the corresponding frequency shift $\Delta\omega = \omega_z - \omega$ is $\Delta\omega/\omega = Q\Delta\alpha/\alpha$, where $Q = 2q/\omega$ is the dimensionless sensitivity coefficient.

For two lines of the same element with the sensitivity coefficients Q_1 and Q_2, the fractional changes $\Delta\mu/\mu$ and $\Delta\alpha/\alpha$ are equal to $\Delta v/(c\Delta Q)$, where $\Delta v = v_1 - v_2$ is the difference of the measured radial velocities of these lines, and $\Delta Q = Q_2 - Q_1$ is the corresponding difference between their sensitivity coefficients [13, 14].

The Q values of atomic transitions observed in quasar spectra are very small, $|Q| \ll 1$ [12]. Similar low sensitivity coefficients were calculated for electro-vibro-rotational transitions in H_2 and CO (for references, see [14]). Small values of Q and ΔQ put tough constraints on optical methods to probe $\Delta\alpha/\alpha$ and $\Delta\mu/\mu$. For instance, at $\Delta\alpha/\alpha \sim 10^{-5}$, the required line position accuracy must be $\sigma_v \lesssim 0.25$ km s^{-1} in accord with the inequality [14]: $\sigma_v/c < (\Delta Q/\sqrt{2})(\Delta\alpha/\alpha)$. A typical error of the line center measurements of an unsaturated absorption line in quasar spectra is about $1/10th$ of the pixel size [15]. For high redshift objects, the UV-Visual Echelle Spectrograph (UVES) at the ESO Very Large Telescope (VLT) provides a pixel size $\Delta\lambda_{\rm pix} \sim 0.06$ Å at $\lambda \sim 5000$ Å, that is $\sigma_v \sim 0.5$ km s^{-1}, which is comparable to the velocity offset due to a fractional change in α at the level of 10^{-5}. This shows that special care and additional calibrations are required to probe $\Delta\alpha/\alpha$ and $\Delta\mu/\mu$ at a level of 10^{-6} by optical methods. Such measurements have been carried out at the VLT/UVES as described in the next section.

3 VLT/UVES Large Program for testing fundamental physics

The ESO Large Programme 185.A–0745 (2010–2013) was especially aimed at testing the hypothetical variability of physical constants [16, 17, 18, 19]. Its prime goal was to study systematic errors in wavelength scales of quasar spectra. For this purpose, quasars were observed almost simultaneously with bright asteroids, whose reflected sunlight spectra contain many narrow features with positions as accurate as a few m s^{-1} [20]. Additionally, bright stars were observed through an iodine gas absorption cell, providing a precise transfer function for part of the wavelength range.

As a result, there were revealed distortions of the wavelength scale with a jigsaw pattern and peak-to-peak amplitude of several hundreds m s^{-1} along the echelle orders. The presence of long range wavelength dependent velocity drifts ranging between ∼0.5 and 1.0 km s^{-1} and showing opposite sign as compared with the Keck/HIRES spectra of quasars was found as well [21].

A stringent bound for $\Delta\alpha/\alpha$ was obtained for the absorber at $z_{\rm abs} = 1.69$ towards the quasar HE2217–2818 [16]. The fractional change of α in this system is $\Delta\alpha/\alpha = (1.3 \pm 2.4_{\rm stat} \pm 1.0_{\rm sys}) \times 10^{-6}$ if Al II λ1670 Å and three Fe II transitions are used, and $\Delta\alpha/\alpha = (1.1 \pm 2.6_{\rm stat}) \times 10^{-6}$ in a slightly different analysis with only Fe II transitions used. Together with another system observed with the UVES/VLT at $z_{\rm abs} = 1.58$ towards HE0001–2340 where $\Delta\alpha/\alpha = (-1.5 \pm 2.6_{\rm stat}) \times 10^{-6}$ [22], and eight HIRES/Keck quasar absorbers with the mean $\Delta\alpha/\alpha = (-0.1 \pm 2.6) \times 10^{-6}$ [23], these values are the tightest bounds to date on α-variation at high redshifts. As seen, they do not show any evidence for changes in α at the precision level of $\sim 3 \times 10^{-6}$ (1σ confidence level, C.L.).

For the electron-to-proton mass ratio, the analysis of the H_2 absorption lines of the $z_{\rm abs} = 2.40$ damped Ly-α system towards HE0027–1836 yields $\Delta\mu/\mu = (2.5 \pm 8.1_{\rm stat} \pm 6.2_{\rm sys}) \times 10^{-6}$ [17]. When corrections to the wavelength dependent velocity drift are applied then $\Delta\mu/\mu = (7.6 \pm 8.1_{\rm stat} \pm 6.3_{\rm sys}) \times 10^{-6}$. At higher redshift $z_{\rm abs} = 4.22$ the analysis of H_2 absorption lines in the spectrum of J1443+2724 gives $\Delta\mu/\mu = (9.5 \pm 5.4_{\rm stat} \pm 5.3_{\rm sys}) \times 10^{-6}$ [24]. These results are consistent with a null μ-variation at the $\sim 2 \times 10^{-5}$ (1σ C.L.) precision level over a lookback time of ≈ 12.4 Gyr (10% of the age of the Universe today).

4 Microwave and submillimeter molecular transitions

Radio astronomical observations allow us to probe variation of the fundamental constants on the cosmological time scale at a level deeper than 10^{-5}. In the microwave range there are a good deal of molecular transitions arising in galactic and extragalactic sources. Electronic, vibrational, and rotational energies in molecular spectra are scaled as $E_{\rm el} : E_{\rm vib} : E_{\rm rot} = 1 : \mu^{1/2} : \mu$. This means that the sensitivity coefficients for pure vibrational and rotational transitions are equal to $Q_{\rm vib} = 0.5$ and $Q_{\rm rot} = 1$. Molecules have also fine and hyperfine structures, Λ-doubling, hindered rotation, accidental degeneracy between narrow close-lying levels of different types and all of them have a specific dependence on the physical constants. Some of these molecular transitions are ∼100 times more sensitive to variations of μ and α than atomic, and electro-vibro-rotational transitions of H_2 and CO which are detected in six quasar absorbers between $z = 1.6$ and 2.7 [25]. In addition, positions of narrow molecular lines arising from cold dark clouds in the Milky Way disk can be measured with uncertainties of $\sigma_v \lesssim 0.01$ km s^{-1} [26], that is, the resulting sensitivity in radio bands is about three orders of magnitude higher as compared with optical spectra.

The molecular transitions with enhanced sensitivity coefficients which are the prime targets for testing the constancy of the fundamental constants by radio astronomical methods were recently reviewed in [14]. For instance, inversion transitions of ammonia NH_3 – one of the most abundant molecules in the interstellar medium – have sensitivity coefficients $Q_\mu = 4.5$ [27]. This enhancement occurs due to the tunneling effect depending on the action S which is proportional to μ^{-1}: the ground state tunneling frequency $\omega \propto e^{-S}$. Observations of the NH_3(1,1) inversion line and five HC_3N rotational lines at $z_{\rm abs} = 0.89$ towards PKS1830–211 [28], as well as the inversion (NH_3) and rotational (CS, H_2CO) lines at $z_{\rm abs} = 0.69$ towards B0218+357 [29] led to constraints (1σ C.L.): $|\Delta\mu/\mu| < 5 \times 10^{-7}$ and $|\Delta\mu/\mu| < 1 \times 10^{-7}$, respectively.

The second molecule which is extremely sensitive to μ-variation and which is observed in galactic and extragalactic molecular clouds is methanol CH_3OH. The sensitivity coefficients Q_μ for different transitions in CH_3OH range from -53 to 42 [30, 31]. A distinctive feature of methanol is strong interaction between the internal (hindered) and overall rotations. Transitions, in which both the internal and overall rotation states are changed, have strongly enhanced Q_μ-factors. However, the magnetic hyperfine structure of methanol transitions which was partly resolved in laboratory measurements [32] puts natural restriction on the methanol method at the level of $\sim 10^{-8}$ in $\Delta\mu/\mu$ tests. The hyperfine coupling in methanol is due to the well known magnetic spin-rotation and spin-spin couplings leading to small line splittings of ∼10 kHz. The large amplitude internal rotation may also lead to a less known magnetic coupling – the so-called spin-torsion coupling – which has not yet been conclusively evidenced.

So far, methanol absorption lines were detected at $z_{\rm abs} = 0.89$ in the gravitationally lensed system PKS1830–211 [33]. This system provides the most stringent limit on changes in μ over a lookback time of ≈ 7.5 Gyr: $|\Delta\mu/\mu| < 2 \times 10^{-7}$ (1σ C.L.) [34].

Cold ($T_{\rm kin} \sim 10$ K) and dense ($n_{\rm H_2} \sim 10^4$ cm^{-3}) molecular cores in the Milky Way disk are another perspective targets to probe μ. The molecular cores are the ammonia emitters exhibiting some of the narrowest ($\Delta v \lesssim 0.2$ km s^{-1} (FWHM)) lines ever observed [35, 36]. The NH_3 line widths Δv of some of them correspond to a pure thermal broadening at a minimum gas temperature of $T_{\rm kin} \approx 8$ K coming mainly from the heating by cosmic rays [37]. A lifetime of molecular cores is $\sim 10^{6-7}$ yr [38], and they are located at regions with different gravitational potentials.

A sample of the molecular cores were studied with the Medicina 32-m, Nobeyama 45-m, and Effelsberg 100-m telescopes in [26, 39, 40]. The main result of these measurements is the most stringent limit on μ-variation for the period of $\sim 10^{6-7}$ yr obtained by astronomical methods [26]: $|\Delta\mu/\mu| < 7 \times 10^{-9}$ (1σ C.L.). This upper limit is comparable with the current constraint stemming from laboratory experiments, $\dot{\mu}/\mu < 6 \times 10^{-16}$ yr^{-1} [41].

An independent test that α and μ may differ between the high- and low-density environments of the Earth and the interstellar medium was performed with CH and OH in [42]. In the Milky Way, the strongest limit to date on α-variation is $|\Delta\alpha/\alpha| < 1.4 \times 10^{-7}$ (1σ C.L.).

Thus, the Einstein heuristic principle of LPI is validated all over the universe, that is, neither α at the level of $\sim$*few* $\times 10^{-6}$, no μ at the level of $\sim$*few* $\times 10^{-7}$ deviates from its terrestrial value for the passed 10^{10} yr. Locally, no statistically significant deviations of $\Delta\mu/\mu$ from zero were found at even more deeper level of $\sim$*few* $\times 10^{-9}$. For the fine structure constant, such limit is $\sim 10^{-7}$.

5 Future prospects

In previous sections we demonstrated that the radio observations of NH_3 and CH_3OH lines are an order of magnitude more sensitive to fractional changes in μ than the optical constraints derived from H_2. However, at cosmological distances there are only five radio molecular absorbers known and all of them are located at $z < 1$, whereas H_2 lines are detected at redshifts $2 \lesssim z \lesssim 4$.

As was emphasized in [14], the improvements in measurements of $\Delta\alpha/\alpha$ and $\Delta\mu/\mu$ at the level of, respectively, 10^{-8} and 10^{-9}, can be achieved if two main requirements will be fulfilled: (*i*) increasing precision of the laboratory measurements of the rest frame frequencies of the most sensitive molecular transitions, and (*ii*) increasing sensitivity and spectral resolution of astronomical observations.

The second requirement is expected to be realized in a couple of years when the Next Generation Very Large Array (ngVLA) will start regular operations [43]. The ngVLA will provide ten times the effective collecting area of the JVLA and ALMA, operating from 1 GHz to 115 GHz, with ten times longer baselines (300 km). The increased sensitivity of the ngVLT by an order of magnitude over the VLA would allow discovery of new molecular absorbers at $z > 1$ and, thus, would extend the sample of targets suitable to test the EEP at early cosmological epochs.

In optical sector, the forthcoming generation of new optical telescopes such as the Thirty Meter Telescope (TMT) and the European Extremely Large

Telescope (E-ELT) equipped by high-resolution ultra-stable spectrographs will significantly improve the constancy limits of fundamental couplings. The future high precision optical measurements should achieve sensitivities of $\sim 10^{-7}$ for individual absorbers. Thanks to a large sample of absorption-line systems, a few times deeper limit is expected for the ensemble average.

In spite of a far higher sensitivity of radio methods as compared to that of next-generation optical facilities, the unresolved (or partly resolved) magnetic hyperfine structure of molecular transitions prevents the radio measurements to achieve the accuracy better than $\sim 10^{-9}$.

For example, the hyperfine structure of several transitions in methanol CH_3OH was recently recorded in the microwave domain using the Fourier transform microwave (FT-MW) spectrometer in Hannover and the molecular beam FT-MW spectrometer in Lille [32]. With the line splitting of $\sim$10 kHz revealed in these laboratory studies, and the difference between the sensitivity coefficients $\Delta Q_\mu \sim 10$ for the 48.372, 48.377, and 60.531 GHz methanol lines observed at $z_{\rm abs} = 0.89$ towards PKS1830–211 [34], one finds the uncertainty of $\Delta\mu/\mu$ of about 3×10^{-8}, which is entirely caused by the unresolved hyperfine structure of methanol lines.

It should be obvious that further progress in radio sector is in need of accurate laboratory measurements of the rest frame molecular frequencies. The required uncertainty of laboratory frequencies is $\lesssim 1$ m s^{-1}. There is currently a shortage of such data. Among molecules with high sensitivity coefficients to changes in μ and α only NH_3 [44] and CH [42, 45] transitions fulfill this requirement.

6 Conclusions

In this short review we highlighted the most important observational results which mark the frontier of most precise spectroscopic measurements of line positions in optical and radio sectors aimed at different tests of the variation of fundamental physical constants by astrophysical methods.

Current null results from the VLT and Keck optical telescopes as well as from different radio telescopes validate the Einstein equivalence principle at a rather deep level of $\sim 10^{-7} - 10^{-6}$ for extragalactic sources and at $\sim 10^{-8}$ within the Milky Way disk. This is a tremendous step forward in experimental justification of basic principles of the general relativity and the standard model of particle physics as compared with the first astrophysical constraint on $|\Delta\alpha/\alpha| < 3 \times 10^{-3}$ towards radio galaxy Cygnus A ($z = 0.057$) obtained 60 years ago by Savedoff [46].

It should be emphasized that both optical and radio methods complement each other and in future will provide independent tests of $\Delta\alpha/\alpha$ and $\Delta\mu/\mu$ variability using the next-generation radio and optical telescopes.

References

1. *E.A. Milne*, Proc. Roy. Soc. A., **158**, 324, 1937.
2. *P.A.M. Dirac*, Nature, **139**, 323, 1937.

3. *A.G. Riess, A.V. Filippenko, P. Challis et al.*, Astron. J., **116**, 1009, 1998.
4. *S. Perlmutter, G. Aldering, G. Goldhaber et al.*, Astrophys. J., **517**, 565, 1999.
5. *J.-P. Uzan*, Living Rev. Rel., **14**, 2, 2011.
6. *S. Liberati*, Class. Quant. Grav., **30**, 133001, 2013.
7. *C.J.A.P. Martin*, Gen. Rel. Grav., **47**, 1843, 2014.
8. *M. Martinelli, E. Calabrese, C.J.A.P. Martin*, J. Cosmol. Astropart. Phys., **11**, 030, 2015.
9. *V.A. Kostelecký, R. Lehnert, M.J. Perry*, Phys. Rev. D, **68**, 123511, 2003.
10. *D.A. Varshalovich, S.A. Levshakov*, J. Exp. Theor. Phys., **58**, 231, 1993.
11. *E.J. Salumbides, M.L. Niu, J. Bagdonaite et al.*, Phys. Rev. A, **86**, 022510, 2012.
12. *V.A. Dzuba, V.V. Flambaum, J.K. Webb*, Phys. Rev. Lett., **82**, 888, 1999.
13. *S.A. Levshakov, M. Dessauges-Zavadsky, S. D'Odorico, P. Molaro et al.*, Mon. Not. Roy. Astron. Soc., **333**, 373, 2002.
14. *M.G. Kozlov, S.A. Levshakov*, Ann. Phys., **525**, 452, 2013.
15. *S.A. Levshakov, M. Centurión, P. Molaro, S. D'Odorico*, Astron. Astrophys., **434**, 827, 2005.
16. *P. Molaro, M. Centurión, J.B. Whitmore et al.*, Astron. Astrophys., **555**, 68, 2013.
17. *H. Rahmani, R. Srianand, N. Gupta et al.*, Mon. Not. Roy. Astron. Soc., **425**, 556, 2013.
18. *P. Bonifacio, H. Rahmani, J.B. Whitmore et al.*, Astron. Nachr., **335**, 83, 2014.
19. *T.M. Evans, M.T. Murphy, J.B. Whitmore et al.*, Mon. Not. Roy. Astron. Soc., **445**, 128, 2014.
20. *P. Molaro, S.A. Levshakov, S. Monai et al.*, Astron. Astrophys., **481**, 559, 2008.
21. *J.B. Whitmore, M.T. Murphy*, Mon. Not. Roy. Astron. Soc., **447**, 446, 2015.
22. *I.I. Agafonova, P. Molaro, S.A. Levshakov, J.L. Hou*, Astron. Astrophys., **529**, A28, 2011.
23. *A. Songaila, L.L. Cowie*, Astrophys. J., **793**, 103, 2014.
24. *J. Bagdonaite, W. Ubachs, M.T. Murphy, J.B. Whitmore*, Phys. Rev. Lett., **114**, 071301, 2015.
25. *P. Noterdaeme, P. Petitjean, R. Srianand et al.*, Astron. Astrophys., **526**, L7, 2011.
26. *S.A. Levshakov, D. Reimers, C. Henkel et al.*, Astron. Astrophys., **559**, A91, 2013.
27. *V.V. Flambaum, M.G. Kozlov*, Phys. Rev. Lett., **98**, 240801, 2007.
28. *C. Henkel, K.M. Menten, M.T. Murphy et al.*, Astron. Astrophys., **500**, 725, 2009.
29. *N. Kanekar*, Astrophys. J. Lett., **728**, L12, 2011.
30. *P. Jansen, L.-H. Xu, I. Kleiner et al.*, Phys. Rev. Lett., **106**, 100801, 2011.

31. *S.A. Levshakov, M.G. Kozlov, D. Reimers*, Astrophys. J., **738**, 26, 2011.

32. *L.H. Coudert, C. Gutlé, T.R. Huet et al.*, J. Chem. Phys., **143**, 044304, 2015.

33. *S. Muller, A. Beelen, M. Guélin et al.*, Astron. Astrophys., **535**, A103, 2011.

34. *N. Kanekar, W. Ubachs, K.M. Menten et al.*, Mon. Not. Roy. Astron. Soc., **448**, L104, 2015.

35. *J. Jijina, P.C. Hyers, F.C. Adams*, Astrophys. J. Suppl., **125**, 161, 1999.

36. *S.A. Levshakov, D. Reimers, C. Henkel*, Astron. Astrophys., **586**, A126, 2016.

37. *P.F. Goldsmith, W.D. Langer*, Astrophys. J., **222**, 881, 1978.

38. *C.W. Lee, P.C. Myers*, Astrophys. J. Suppl., **123**, 233, 1999.

39. *S.A. Levshakov, P. Molaro, A.V. Lapinov et al.*, Astron. Astrophys., **512**, A44, 2010.

40. *S.A. Levshakov, A.V. Lapinov, C. Henkel et al.*, Astron. Astrophys., **524**, A32, 2010.

41. *M.C. Ferreira, M.D. Julião, C.J.A.P. Martins et al.*, Phys. Rev. D, **86**, 125025, 2012.

42. *S. Truppe, R.J. Hendricks, S.K. Tokunaga et al.*, Nature Commun., **4**, 2600, 2013.

43. *G.C. Bower, P. Demorest, J. Braatz et al.*, arXiv: astro-ph.HE/1510.06432, 2015.

44. *S.G. Kukolich*, Phys. Rev., **156**, 83, 1967.

45. *S. Truppe, R.J. Hendricks, S.K. Tokunaga et al.*, J. Molec. Spectrosc., **300**, 70, 2014.

46. *M.P. Savedoff*, Nature, **178**, 688, 1956.