

Fundamental Physical Constants at Low and High Redshifts

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Abstract. Spacetime variations of physical constants can be associated with the existence of Higgs-like scalar field(s) that couple non-universally to the baryonic matter. Recent results of astronomical spectral measurements of the fractional changes in the electron-to-proton mass ratio, $\mu = m_e/m_p$, at low ($z \sim 0$) and high ($z \sim 6.5$) redshifts are discussed. It is shown that the distribution of the most accurate estimates of $\Delta\mu/\mu = (\mu_{\text{obs}} - \mu_{\text{lab}})/\mu_{\text{lab}}$ ranging between $z = 0$ and $z \sim 1100$ can be approximated by a power law $\Delta\mu/\mu = k_\mu(1+z)^p$, with $k_\mu = (1.7 \pm 0.3) \times 10^{-8}$ and $p = 1.99 \pm 0.03$, implying a dynamical nature of the scalar field(s).

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1 Introduction

The suggestion that the physical constants may vary on the cosmological time scale can be traced as far back as 1937, when Milne (1937); Dirac (1937) argued about possible changes in the gravitational constant G during the lifetime of the universe. Modern physics considers the masses of quarks and leptons as a result of their Yukawa coupling to the scalar Higgs field. Other scalar fields, which are proposed to explain the phenomena of dark energy and dark matter, can also couple to the standard baryonic matter and, hence, change the masses of elementary particles. Since the proton and neutron masses are mainly determined by the binding energy of quarks (Uzan 2011), the changes of their masses due to dynamical scalar fields are much smaller compared to the effect of altering m_e (Kujat & Scherrer 2000). Thus, values of the fine structure constant, $\alpha = e^2/\hbar c$, and the electron to proton mass ratio, $\mu = m_e/m_p$, measured at different physical and cosmological conditions can be used to probe the hidden scalar fields.

Nowadays, the search for hypothetical variations of α and μ is among the most extensively studying problems in laboratory and cosmic physics.

The unprecedentedly sensitive limits on the temporal drift of these dimensionless constants achieved for the passed decades in laboratory experiments are of one part in $10^{15} - 10^{16}$ per year (Blatt et al. 2008; Ferreira et al. 2012; Schwarz et al. 2020).

Astrophysical studies of extragalactic objects at low ($z \sim 0$) and high ($z \sim 1 - 7$) redshifts constrain the fractional changes in $\Delta\alpha/\alpha = (\alpha_{\text{obs}} - \alpha_{\text{lab}})/\alpha_{\text{lab}}$ and $\Delta\mu/\mu = (\mu_{\text{obs}} - \mu_{\text{lab}})/\mu_{\text{lab}}$ at the same order of magnitude (Molaro et al. 2008; Agafonova et al. 2011; Kanekar et al. 2015; Levshakov et al. 2019) if we assume a linear drift of the physical constants with cosmic time. New optical spectral observations with two high-resolution spectrographs ESPRESSO/VLT (Lee et al. 2020) and HIRES/E-ELT (Marconi et al. 2018) are planning to put ever deeper constraints on α - and μ -variations.

A recent analysis of the ionization processes at redshift $z \sim 1100$ which are responsible for the temperature and polarization anisotropies of the cosmic microwave background (CMB) radiation has shown that the value of the Hubble constant H_0 correlates with the electron mass (Hart & Chluba 2020). As a result, an increased effective electron mass at the epoch of recombination, $m_{e,z} = (1.0190 \pm 0.0055)m_{e,0}$, yields $H_0 \simeq 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ — the value shifted with respect to $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ which is based on the standard Λ CDM model (Planck Collaboration et al. 2020). Such a 2% increasing of the electron mass at $z \sim 1100$ may alleviate the difference between the Hubble constant measured at $z \lesssim 1$, $H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Riess et al. 2019), and the CMB value.

2 Constraints on the Time Variation of μ

Note that the spacetime variation of the electromagnetic fine structure constant α should be much smaller than that of μ (Yoo & Scherrer 2003). In the following we will consider α unchangeable and put $\Delta\alpha/\alpha = 0$.

The variation of μ can be probed by comparing the relative frequencies of different molecular transitions as was originally suggested in 1975 by Thompson (1975). Later on, it was shown that transitions within the molecular bands have different sensitivities to the variation of μ (Varshalovich & Levshakov 1993). The corresponding sensitivity coefficients Q for the Lyman and Werner transitions of H_2 are typically ~ 0.01 and differ in sign (Varshalovich & Levshakov 1993; Ubachs et al. 2007). The H_2 absorption lines detected in quasar spectra (Levshakov & Varshalovich 1985; Balashev et al. 2020) give the following estimation

of $\Delta\mu/\mu$:

$$\Delta\mu/\mu = (R_{ij} - R_{ij}^0)/[R_{ij}^0(Q_j - Q_i)] , \quad (1)$$

where $R_{ij} = (\lambda_i/\lambda_j)_z$ is the ratio of two H₂ lines at the epoch z , R_{ij}^0 – at $z = 0$, and Q_i, Q_j are the sensitivities of the wavelengths λ_i, λ_j to the variation of μ . This so-called *H₂ method*, being applied to optical spectra of quasars, provides the mean value of $\langle\Delta\mu/\mu\rangle = (-2.5 \pm 5.3) \times 10^{-6}$ in the interval from $z = 2.05$ to $z = 4.22$ (Levshakov et al. 2020).

The microwave and submillimeter astronomical spectra are essentially more sensitive to variations in μ than the H₂ lines (Kozlov & Levshakov 2013). For instance, the *NH₃ method* (Flambaum & Kozlov 2007) yields

$$\Delta\mu/\mu = (V_{\text{rot}} - V_{\text{inv}})/[c(Q_{\text{inv}} - Q_{\text{rot}})] , \quad (2)$$

where the observed radial velocity V_{inv} of the inversion transition of NH₃(1,1) with $Q_{\text{inv}} = 4.46$ is compared with a suitable rotational radial velocity V_{rot} of another molecule co-spatially distributed with ammonia and having $Q_{\text{rot}} = 1$, and c is the speed of light. In the Milky Way disk, the *NH₃ method* provides $\langle\Delta\mu/\mu\rangle = (2 \pm 6) \times 10^{-9}$ (Levshakov et al. 2013).

A wide range of Q -values (from $\simeq -15$ to $\simeq 45$) of methanol CH₃OH lines was deduced in Jansen et al. (2011); Levshakov et al. (2011). Any two transitions of CH₃OH with different sensitivity coefficients Q_i and Q_j give the following estimate of $\Delta\mu/\mu$:

$$\Delta\mu/\mu = (V_j - V_i)/[c(Q_i - Q_j)] , \quad (3)$$

where V_j and V_i are the apparent radial velocities of the corresponding methanol transitions. The deepest limits on $\Delta\mu/\mu$ were obtained by the *CH₃OH method* for the Galactic cloud L1498 (Daprà et al. 2017) and the $z = 0.89$ gravitational lens (Kanekar et al. 2015): $\Delta\mu/\mu = (-3 \pm 2) \times 10^{-8}$ and $(3 \pm 6) \times 10^{-8}$, respectively.

Finally, to probe $\Delta\mu/\mu$ by spectroscopic methods at very high redshifts ($z \gtrsim 6$) a fine structure transition method (FST) was proposed in Levshakov et al. (2008). It is based on the analysis of the radial velocity offsets between CO rotational lines and [C I] and/or [C II] fine-structure transitions. Under assumption that $\Delta\alpha/\alpha = 0$, it gives Levshakov et al. (2020):

$$\Delta\mu/\mu = \Delta V/c , \quad (4)$$

where ΔV is the radial velocity offset, $\Delta V = V_{\text{fs}} - V_{\text{rot}}$. Three estimates of $\Delta\mu/\mu$ at $z = 6.003, 6.419, \text{ and } 6.519$ by the FST method provide a weighted mean value of $\langle\Delta\mu/\mu\rangle = (0.7 \pm 1.2) \times 10^{-5}$ at $\bar{z} = 6.3$ (Levshakov et al. 2020).

All available values of $\Delta\mu/\mu$, ranging between $z = 0$ and $z \sim 1100$, were put together in Fig. 3 in Levshakov et al. (2020). Here, in Fig. 1, we reproduce this

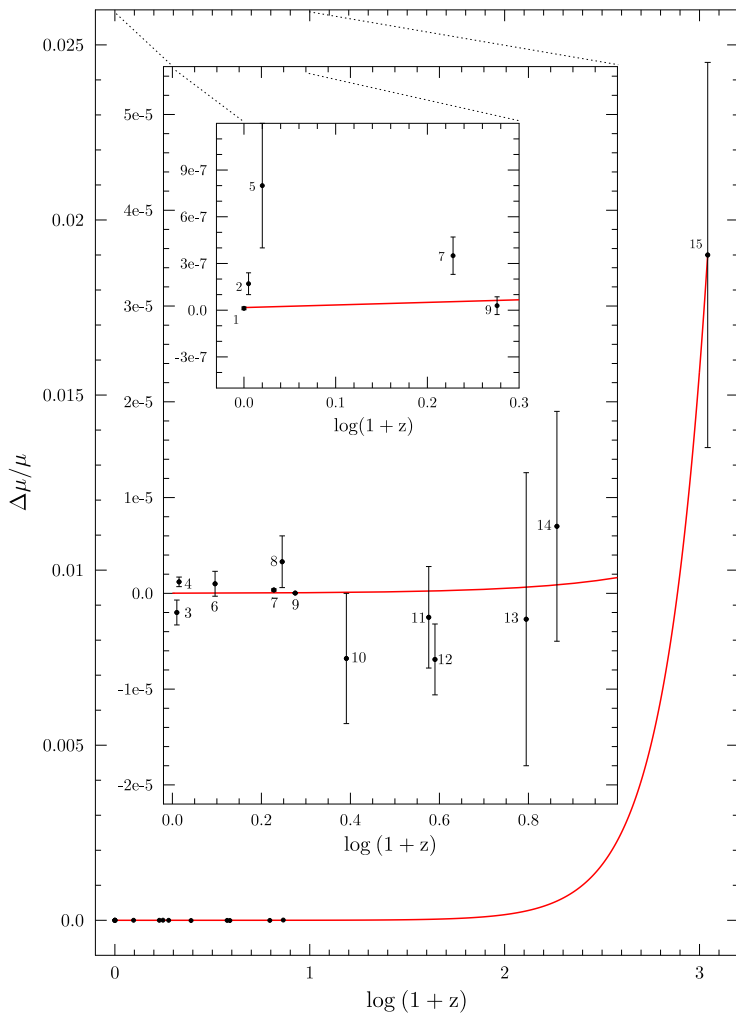


Fig. 1. Constraints on the fractional changes in μ (dots with 1σ error bars) as a function of redshift z in units of $\log_{10}(1+z)$. Two inserts zoom consequently the corresponding parts of the data sample using different horizontal and vertical scales. Shown by red is a two-parameter regression curve $\Delta\mu/\mu = k_\mu(1+z)^p$ with $k_\mu = (1.7 \pm 0.3) \times 10^{-8}$ and $p = 1.99 \pm 0.03$ (1σ). Data points 1,2,6-15 are taken from Levshakov et al. (2020), and 3-5 from the present paper. Points 1-5 at $z = 0$ are slightly shifted with respect to each other to resolve blending.

compilation with a slightly updated dataset: instead of one $\Delta\mu/\mu$ value averaged over the whole Triangulum galaxy M33 ($D \simeq 800$ kpc) we use three $\Delta\mu/\mu$ values calculated on base of the CO(2-1) and [C II] emission lines in regions at different galactocentric distances: $R_c = 0, 2,$ and 3.5 kpc. The distribution of the updated data points (shown by dots with 1σ error bars in Fig. 1) was approximated by a simple power law

$$\Delta\mu/\mu = k_\mu(1+z)^p, \quad (5)$$

which gives $k_\mu = (1.7 \pm 0.3) \times 10^{-8}$ and $p = 1.99 \pm 0.03$ (1σ). The corresponding regression curve is shown by red in Fig. 1.

An important point to note is that the revealed z -dependence of μ crucially depends on the CMB estimate of the electron mass at $z \sim 1100$.

It is obvious that to verify the redshift dependence of μ a more refined analysis of the CMB anisotropies is needed along with more accurate spectral measurements at lower redshifts. The required uncertainty of the molecular line position measurements should be less or about 10 m s^{-1} which can be achieved with the existing radio astronomical facilities in observations of objects in the local Universe ($z \lesssim 1$).

Bibliography

- Agafonova, I. I., Molaro, P., Levshakov, S. A., & Hou, J. L. 2011, *A&A*, 529, A28
- Balashev, S. A., Ledoux, C., Noterdaeme, P., et al. 2020, *MNRAS*, 497, 1946
- Blatt, S., Ludlow, A. D., Campbell, G. K., et al. 2008, *Phys. Rev. Lett.*, 100, 140801
- Daprà, M., Henkel, C., Levshakov, S. A., et al. 2017, *MNRAS*, 472, 4434
- Dirac, P. A. M. 1937, *Nature*, 139, 323
- Ferreira, M. C., Julião, M. D., Martins, C. J. A. P., & Monteiro, A. M. R. V. L. 2012, *Phys. Rev. D*, 86, 125025
- Flambaum, V. V. & Kozlov, M. G. 2007, *Phys. Rev. Lett.*, 98, 240801
- Hart, L. & Chluba, J. 2020, *MNRAS*, 493, 3255
- Jansen, P., Xu, L.-H., Kleiner, I., Ubachs, W., & Bethlem, H. L. 2011, *Phys. Rev. Lett.*, 106, 100801
- Kanekar, N., Ubachs, W., Menten, K. M., et al. 2015, *MNRAS*, 448, L104
- Kozlov, M. G. & Levshakov, S. A. 2013, *Annalen der Physik*, 525, 452
- Kujat, J. & Scherrer, R. J. 2000, *Phys. Rev. D*, 62, 023510
- Lee, C.-C., Webb, J. K., Carswell, R. F., & Milakovic, D. 2020, arXiv e-prints, arXiv:2008.02583
- Levshakov, S. A., Kozlov, M. G., & Agafonova, I. I. 2020, *MNRAS*, 498, 3624

- Levshakov, S. A., Kozlov, M. G., & Reimers, D. 2011, *ApJ*, 738, 26
- Levshakov, S. A., Ng, K. W., Henkel, C., et al. 2019, *MNRAS*, 487, 5175
- Levshakov, S. A., Reimers, D., Henkel, C., et al. 2013, *A&A*, 559, A91
- Levshakov, S. A., Reimers, D., Kozlov, M. G., Porsev, S. G., & Molaro, P. 2008, *A&A*, 479, 719
- Levshakov, S. A. & Varshalovich, D. A. 1985, *MNRAS*, 212, 517
- Marconi, A., Allende Prieto, C., Amado, P. J., et al. 2018, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 10702, *Ground-based and Airborne Instrumentation for Astronomy VII*, ed. C. J. Evans, L. Simard, & H. Takami, 107021Y
- Milne, E. A. 1937, *Proceedings of the Royal Society of London Series A*, 158, 324
- Molaro, P., Reimers, D., Agafonova, I. I., & Levshakov, S. A. 2008, *European Physical Journal Special Topics*, 163, 173
- Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2020, *A&A*, 641, A6
- Riess, A. G., Casertano, S., Yuan, W., Macri, L. M., & Scolnic, D. 2019, *ApJ*, 876, 85
- Schwarz, R., Dörscher, S., Al-Masoudi, A., et al. 2020, *Physical Review Research*, 2, 033242
- Thompson, R. I. 1975, *Astrophys. Lett.*, 16, 3
- Ubachs, W., Buning, R., Eikema, K. S. E., & Reinhold, E. 2007, *Journal of Molecular Spectroscopy*, 241, 155
- Uzan, J.-P. 2011, *Living Reviews in Relativity*, 14, 2
- Varshalovich, D. A. & Levshakov, S. A. 1993, *Soviet Journal of Experimental and Theoretical Physics Letters*, 58, 237
- Yoo, J. J. & Scherrer, R. J. 2003, *Phys. Rev. D*, 67, 043517