A new constraint on cosmological variability of the proton-to-electron mass ratio*

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ABSTRACT

Exotic cosmologies predict variability of the fundamental physical constants over the cosmic time. Using the VLT/UVES high resolution spectra of the quasar Q0347–3819 and unblended electronic-vibrational-rotational lines of the H2 molecule identified at $z_{abs} = 3.025$ we test possible changes in the proton-to-electron mass ratio $\mu_0 = m_p/m_e$ over the period of $\sim 11$ Gyr. We obtained a new constraint on the time-averaged variation rate of the $\mu_0$ ratio of about $0.004\%$ implies that since the time when the H2 spectrum was formed at $z_{abs} = 3.025$, $\mu_0$ has not changed by more than a few thousands of a percent.

Key words: cosmology: observations – elementary particles – quasars: absorption lines – quasars: individual: Q0347–3819

1 INTRODUCTION

Kaluza-Klein (KK) type models (Super-symmetric Grand Unification Theory, Super string models, etc.) unify gravity with other fundamental forces. These models predict variations of the fundamental physical constants over the cosmological evolution (for a review, see, e.g., Okun’ 1991). Variations of the coupling constants of strong and electroweak interactions would affect the masses of the elementary particles in a way which depends on the adopted scenario for the expanding universe. The model parameters of these theories can be constrained by observations. One possibility to test values of the physical constants at different cosmological epochs is to study high resolution spectra of extragalactic objects (Savedoff 1956).

Such analysis has been recently carried out by a number of authors (see, e.g., Varshalovich, Potekhin & Ivanich 2000, and references cited therein), and a possible variation of the fine-structure constant, $\alpha_0 = e^2/hc$, at a level of $\Delta\alpha/\alpha_0 = (-0.72 \pm 0.18) \times 10^{-5}$ was announced by Webb et al. (2001) who analyzed fine-splitting lines in quasar spectra.

The first restriction on the variability of the proton-to-electron mass ratio $\mu_0 = m_p/m_e$, stemming from quasar spectra $|\Delta \mu/\mu_0| < 0.13$ (1σ c.l.) was obtained by Pagel (1977) who compared the observational wavelengths of H1 and metals as previously proposed by Thompson (1975). However, the derived upper limit on $\mu_0$ depends on the assumption that all elements have the same fractional ionization ratios and trace the same volume elements along the respective line of sight. This assumption may not be true in general especially for QSO absorbers where complex absorption-line profiles are observed at high spectral resolution.

The proton-to-electron mass ratio can be estimated more accurately from high redshift molecular hydrogen systems. With some modifications, such measurements were performed for the $z_{abs} = 2.811$ H2 system from the spectrum of PKS 0528–250 by Foltz, Chaffe & Black (1988), Varshalovich & Levshakov (1993), Cowie & Songaila (1995), and by Potekhin et al. (1998) who set the most stringent limit of $|\Delta \mu/\mu_0| < 1.8 \times 10^{-4}$ (1σ c.l.).

In this paper, we present a new upper limit on the variation rate of the proton-to-electron mass ratio obtained from the analysis of a new H2 system found at $z_{abs} = 3.025$ toward the quasar Q0347–3819.

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The present value of the proton-to-electron mass ratio is $\mu_0 = 1836.1526670$ (Mohr & Taylor 2000).
**2 OBSERVATIONS**

High resolution spectra of the quasar Q0347–3819 were obtained during UVES commissioning at the VLT 8.2m ESO telescope and are described in detail by D’Odorico, Dessauges-Zavadsky & Molaro (2001) and Levshakov et al. (2002, LDDM hereinafter). The spectrum resolution is FWHM $\approx 7.0$ km s$^{-1}$ and 5.7 km s$^{-1}$ in the UV and near-IR ranges, respectively. The signal-to-noise ratio per resolution element in the UV range is $S/N \sim 10–40$.

We identified more than 80 H$_2$ molecular lines in a damped Ly$\alpha$ system (DLA hereinafter) at $z_{\text{abs}} = 3.025$ toward Q0347–3819 (LDDM). Some of them are not suitable for further analysis due to H$_1$ Ly$\alpha$ forest contamination. However, we selected 15 unblended H$_2$ lines (shown in Fig. 1) which provide the most accurate line center measurements to set an upper limit on possible changes of $\mu_0$.

We would like to emphasize that our analysis of the $z_{\text{abs}} = 3.025$ DLA has shown that all the H$_2$ line profiles can be adequately described with a unique value of $z_{H_2} = 3.024855 \pm 0.000005$, which implies that no assumption on the variability of $\mu_0$ is needed or statistically justified. Observations show that the ratio $\Delta \mu/\mu_0 \equiv (\mu_z - \mu_0)/\mu_0$ is zero. The analysis presented below has the objective to estimate at what accuracy $\Delta \mu/\mu_0 = 0$.

**3 DATA ANALYSIS AND RESULTS**

For measurements of the absorption line centers in QSO spectra, there are three principal sources of statistical errors

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5 The damped Ly$\alpha$ systems are believed to originate in the intervening galaxies or proto-galaxies located at cosmological distances (e.g. Wolfe et al. 1995).

6 Based on the H$_2$ laboratory wavelengths given in Abgrall & Roueff (1989).
caused both by the data reduction procedure and by statistical fluctuations in the recorded counts. First, all echelle data must be rebinned to constant wavelength bins in order to combine different spectra and hence to increase the signal-to-noise ratio. Such resampling changes statistical properties of the noise and introduces correlations between the data point values. The correlation coefficient of about +0.8 was determined by using ‘continuum windows’ in the Lyα forest which were fitted by a low order polynomial. The accuracy \( \delta_c \) of the local continuum (which may deviate from the common continuum in the Lyα forest region) was estimated during the fitting procedure described below.

For a given \( \mathrm{H}_2 \) line, the number of pixels involved in the analysis corresponds to the number of points in the line profile shown in Fig. 1. To measure the line centers we used a method that matches the observed profiles with the synthesized ones to estimate the set of model parameters. Our previous analysis of the line profiles of different elements identified in the \( z_{\text{abs}} = 3.025 \) \( \mathrm{H}_2 \)-bearing cloud has shown that both low ions and \( \mathrm{H}_2 \) have the same simple velocity structure of the main component – a narrow asymmetrical core with a common broadening parameter \( b_{\text{H}_2} = 2.80 \pm 0.45 \text{ km s}^{-1} \) (LDDM). Thus in our present study we also used a simple one-component model with four free parameters: the center, the width, the intensity of the absorption line and the local continuum displacement \( \delta_c = \Delta C/C \) (this technique was successfully used in the study of metal lines in the Lyα forest by Molaro et al. 2001). The set of initial parameters then was adjusted until a satisfactory fit could be achieved. The objective function was augmented with the penalty function in the form [cf. Eqs. (13) and (14) in LDDM]:

\[
\psi = \left( \frac{b - b_{\text{H}_2}}{\sigma_{b_{\text{H}_2}}} \right)^2 ,
\]

(1)

where \( b_{\text{H}_2} = 2.80 \pm 0.45 \text{ km s}^{-1} \) and \( \sigma_{b_{\text{H}_2}} = 0.45 \text{ km s}^{-1} \). To evaluate statistical errors, Monte Carlo analysis was performed in the same way as described in Appendix A in LDDM. The results of these calculations are presented in columns (4) and (5) of Table 1. It is seen that for the selected \( \mathrm{H}_2 \) lines \( \delta_c \approx 1\% \). This means that the \( \mathrm{H}_2 \) lines involved in

### Table 1. \( \mathrm{H}_2 \) lines at \( z_{\text{abs}} = 3.025 \) toward Q0347–3819 and sensitivity coefficients \( K \).

| \( J \)     | Line     | \( \lambda_{\text{obs}}^a, \text{Å} \) | \( \Delta C/C^b, \% \) | \( \lambda_{\text{obs}}^c, \text{Å} \) | \( z \) | \( K \) |
|----------|----------|---------------------------------------|------------------------|---------------------------------------|-------|------|
| 1        | W3-0Q    | 947.4218 ± 0.0005                     | 0.9 ± 0.2              | 3813.2653 ± 0.0041                   | 0.024887(5) | 0.0217427(8) |
|          | L1-0P    | 1094.0922 ± 0.0051                     | 0.8 ± 0.1              | 4403.4575 ± 0.0077                   | 0.02491(2)  | −0.003282(1) |
|          | L3-0R    | 1065.4053 ± 0.0003                     | 0.8 ± 0.1              | 4290.3051 ± 0.0030                   | 0.024885(3) | 0.0112256(4) |
|          | L3-0P    | 1064.6056 ± 0.0005                     | 0.9 ± 0.2              | 4284.9249 ± 0.0033                   | 0.024894(4) | 0.0102682(4) |
|          | L7-0R    | 1013.4412 ± 0.0020                     | 0.8 ± 0.1              | 4078.9785 ± 0.0025                   | 0.024898(9) | 0.03050(1)    |
|          | L10-0P   | 982.8340 ± 0.0006                      | 0.8 ± 0.1              | 3955.8049 ± 0.0051                   | 0.024896(6) | 0.04054(6)    |
| 2        | W0-0R    | 1009.0233 ± 0.0007                     | 0.8 ± 0.1              | 4061.2194 ± 0.0061                   | 0.024901(7) | −0.0050567(7) |
|          | W0-0Q    | 1010.9380 ± 0.0001                     | 0.8 ± 0.1              | 4068.9088 ± 0.0053                   | 0.024885(6) | −0.0068461(2) |
|          | W1-0Q    | 987.9744 ± 0.0020                      | 0.9 ± 0.1              | 3976.4943 ± 0.0049                   | 0.02490(1)  | 0.0039207(2)  |
|          | L3-0R    | 1064.9933 ± 0.0009                     | 1.0 ± 0.2              | 4286.4755 ± 0.0098                   | 0.02488(1)  | 0.0097740(5)  |
|          | L4-0R    | 1051.4981 ± 0.0004                     | 0.8 ± 0.1              | 4232.1793 ± 0.0085                   | 0.024904(8) | 0.015220(1)   |
|          | L5-0R    | 1038.6855 ± 0.0032                     | 0.8 ± 0.1              | 4180.6048 ± 0.0070                   | 0.024901(1) | 0.020209(3)   |
| 3        | L4-0R    | 1053.9770 ± 0.0011                     | 0.8 ± 0.1              | 4242.1419 ± 0.0028                   | 0.024890(5) | 0.012837(2)   |
|          | L6-0R    | 1029.8832 ± 0.0016                     | 0.8 ± 0.1              | 4141.5758 ± 0.0031                   | 0.024921(7) | 0.022332(7)   |
|          | L12-0R   | 967.6752 ± 0.0021                      | 0.8 ± 0.1              | 3894.7974 ± 0.0039                   | 0.02490(1)  | 0.0440(2)     |

Notes: \(^a\) listed values are from Abgrall et al. (1993a, 1993b); \(^b\) the local continuum deviation with 1σ error; \(^c\) the error is estimated from the comparison between the data in Abgrall & Roueff (1989) and Abgrall et al. (1993a, 1993b); \(^d\) 1σ standard deviations are shown in parenthesis (last digits after a decimal point), e.g. 3.024887(5) means 3.024887 ± 0.000005.
sponding line centers measured in a quasar spectrum. These coefficients have been calculated by Varshalovich & Levshakov (1993) and recent version of the procedure to calculate the proton-to-electron mass ratio. Both methods give results in good agreement. The most accurate value of the proton-to-electron mass ratio is \( \mu/\mu_0 \). The accuracy of this value has been improved by Potekhin et al. (2002) using the method of error propagation (\( Y_{n,n} \) values were considered to be accurate to \( k \) decimal places and their rounding errors were set to \( 0.5 \times 10^{-k} \)). It should be noted that although transitions between the excited states of the \( \text{H}_2 \) molecule have higher wavelength-to-mass sensitivity coefficients, their accuracy is much lower as compared with the low-\( J \) transitions. In linear approximation
\[
\Delta z = \bar{z} + \kappa (K_\text{c} - \bar{K}),
\]
(3)
where \( \kappa = (1 + \bar{z}) \Delta \mu/\mu_0 \) with \( \bar{z} \) and \( \bar{K} \) being the mean redshift and the mean sensitivity coefficient, respectively.

The linear regression in the form (3) was firstly calculated for the complete sample of the \( \text{H}_2 \) lines (Table 1) where transitions from the \( J = 1, 2 \) and 3 levels are combined. The obtained result \( (\Delta \mu/\mu_0)_{J=1,2+3} = \pm 2.5 \times 10^{-5} \) (which is consistent with the value independently found by Ivanchik et al. 2002) shows a “possible variation” of \( \mu_0 \) at the 1.6\( \sigma \) level. However, if we consider \( \text{H}_2 \) transitions from individual \( J \) levels, then the weighted mean redshifts reveal a gradual shift in the radial velocity for features arising from progressively higher rotational levels: \( z_{J=3}^{\mu_0} = 3.024895(3) \), and \( z_{J=2}^{\mu_0} = 3.024904(4) \). The \( \text{H}_2 \) lines with changing profiles and small velocity shifts as \( J \) increases were also observed in our Galaxy in the direction of \( \zeta \) Ori A by Jenkins & Peimbert (1997) who suggested that these \( \text{H}_2 \) lines are formed in different zones of a postshock gas.

Albeit the \( z_{J=1}^{\mu_0} \) and \( z_{J=2}^{\mu_0} \) values are consistent within 1\( \sigma \) intervals, the difference between \( z_{J=1}^{\mu_0} \) and \( z_{J=2}^{\mu_0} \) is essential and equals \( 1.0 \pm 0.3 \) km s\(^{-1} \). If we now exclude from the regression analysis levels with \( J = 3 \), then \( (\Delta \mu/\mu_0)_{J=1,2} \)
(2.1±3.6)×10⁻⁵. (The use of samples with H₂ lines arising from the same rotational levels would be more reasonable to estimate Δµ/µ₀, but in our case the sample size is rather small and we have to combine the J = 1 and J = 2 levels to increase accuracy). This linear regression is shown by the solid line in Fig. 2 while two dashed lines correspond to the 1σ deviations of the slope parameter κ.

We also calculated the probability density functions of Δµ/µ₀ for two samples of the H₂ lines (with J = 1, 2, 3, and J = 1, 2) using statistical Monte Carlo simulations which suggest that the errors σ₁ and σ₂c are normally distributed around the mean values of z and K with the dispersions equal to their probable errors listed in Table 1. The result is presented in Fig. 3. It is clearly seen that small changes in the radial velocity with increasing J cause the difference between these two probability density functions and thus may mimic a shift in Δµ/µ₀.

From these calculations we find |Δµ/µ₀| < 5.7×10⁻⁵ (1σ) which is about three times stronger as compared with the value estimated by Potekhin et al. (1998).

Both constraints on the variation of the mp/me ratio are in good agreement with the limit on the variability of the product of the fine-structure constant, nuclear g factor of the proton and the masses of the electron and proton Δln ((α² mp/me/µ₀) = (1.2±1.8)×10⁻⁴ which was set by de Bruyn, O’Dea & Baum (1996) from the measurements of the redshifts of the H₁ 21 cm line and the optical resonance absorption lines observed at zabs = 3.38 in the DLA toward Q0201+113. The same order of magnitude restrictions to Δln ((α² mp/me/µ₀) were found from other DLAs detected at zabs = 0.524 (Q0235+164), 0.692 (3C286), 1.944 (Q1157+014), and 2.038 (Q0458-020) (see Table 4 in de Bruyn et al. 1996), and even stronger limit of (0.7±1.1)×10⁻⁵ at zabs = 1.776 (Q1331+170) was set by Cowie & Songaila (1995). Comparison of H₁ 21 cm and molecular absorption (CO, 13CO, C₁₈O, CS, HCO⁺, and HCN) also yields very tight constrains on the ratio |Δµ/µ₀| ≈ 0.7×10⁻⁵ at zabs = 0.2467 and 0.6847 toward Q1413+135 and Q0218+357, respectively (Murphy et al. 2001).

In our calculations the 1σ confidence interval to Δµ/µ₀ was set as

\[-1.5×10^{-5} < \Delta \mu/\mu_0 < 5.7 \times 10^{-5}\]

For a cosmological model with Ω_M = 0.3, ΩΛ = 0.7, and H₀ = 72 km s⁻¹ Mpc⁻¹, the look-back time for zabs = 3.025 is 11.2 Gyr [see, e.g., equation (16) in Carroll, Press, & Turner 1992]. This leads to the restriction

\[|\mu/\mu_0| < 5 \times 10^{-15} \text{ yr}^{-1}\]

on the variation rate of µ₀.

4 CONCLUSIONS

We have obtained a new constraint on the variation rate of the proton-to-electron mass ratio of Δµ/µ₀ = (2.1 ± 3.6)×10⁻⁵ at zabs = 3.025 toward Q0347–3819 (Δt ≈ 11 Gyr). The accuracy is a factor of 3 higher as compared with the measurements in another H₂-bearing cloud at zabs = 2.811 toward Q0528–250 (Potekhin et al. 1998). Both measurements show no statistically significant changes of µ₀ on space and time coordinates.

Since the functional dependence of the masses of proton and electron on the fine-structure constant is unknown, we are not able to compare directly our result with changes in α at the level of 0.7×10⁻⁵ found by Webb et al. (2001).

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