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Time dependence of the proton-to-electron mass ratio ☆

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Abstract

We have measured with high precision the position of 79 molecular hydrogen absorption lines of Lyman and Werner bands from two absorption systems at $z_{\rm abs} = 2.594733$ and 3.024899, in the spectra of quasars Q 0405–443 and Q 0347–383, respectively, in order to constrain the cosmological variation of the proton-to-electron mass ratio, $\mu = m_{\rm p}/m_{\rm e}$. Data are of the highest spectral resolution ($R = 53\,000$) and signal to noise ratio (S/N = 30–70) for such quasars. The absorption lines are not saturated and their profiles can be modelled as simple Gaussian functions. We find a correlation between the observed redshift of the lines and the sensitivity of the line positions to a change in μ. This can be interpreted as a variation of μ with $\Delta\mu/\mu = (2.97 \pm 0.74) \times 10^{-5}$ over the past $\sim$12 Gyrs. As this result is based on two systems one cannot rule out that unknown systematics could cause a false-alarm detection. Thus the result needs to be confirmed with additional data. It is also very important to improve the accuracy of the laboratory wavelengths as the significance of our result depends on the accuracy to which they are known. ***To cite this article: P. Petitjean et al., C. R. Physique 5 (2004).***

Résumé

Variation avec le temps cosmique du rapport de la masse du proton à celle de l'électron. Nous avons mesuré avec une très grande précision la position de 79 raies des séries Lyman et Werner de la molécule d'hydrogène, associées à deux systèmes d'absorption à décalage spectral $z_{\rm abs} = 2{,}594733$ et 3,024899, observés dans le spectre des quasars Q 0405–443 and Q 0347–383, respectivement, dans le but de contraindre la variation avec le temps cosmique du rapport de la masse du proton à celle de l'électron, $\mu = m_{\rm p}/m_{\rm e}$. Les données sont de qualité exceptionnelle pour des quasars ; la résolution spectrale est de $R = 53\,000$ et le rapport signal à bruit S/B = 30–70. Les raies d'absorption ne sont pas saturées et leur profil peut être modélisé par une simple gaussienne. Nous trouvons qu'une corrélation existe entre le décalage spectral des raies et le coefficient de sensibilité des longueurs d'onde à une variation de μ. Cette corrélation peut être interprétée comme une variation de μ, $\Delta\mu/\mu = (2{,}97 \pm 0{,}74) \times 10^{-5}$, au cours des $\sim$12 derniers milliards d'années écoulés. Il est important d'obtenir des données indépendantes. En effet, l'existence d'une anticorrélation entre λ et K rend difficile la mise en évidence des erreurs

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systématiques qui pourraient dominer le résultat. En outre, les erreurs sur les longueurs d'onde mesurées au laboratoire sont difficiles à estimer. ***Pour citer cet article : P. Petitjean et al., C. R. Physique 5 (2004).***

Keywords: Cosmology: observations; Quasars: absorption lines; Individual: Q 0405–443, Q 0347–383

Mots-clés : Cosmologie : observations ; Galaxies : halos ; Quasar : raies d'absorption ; Objets : Q 0405–443, Q 0347–383

1. Introduction

A considerable amount of interest in the possibility of time variations of the fine structure constant, $\alpha = e^2/\hbar c$, has been generated by recent observations of quasar absorption line systems. Using a new and sensitive method, the so-called Multi-Multiplet analysis [1,2], Murphy et al. [3] have claimed that α could have varied over the redshift range $0.2 < z < 3.7$ with $\Delta\alpha/\alpha = (-0.543 \pm 0.116) \times 10^{-5}$. Although this measurement has been challenged very recently, Chand et al. [4] deriving $\Delta\alpha/\alpha = (-0.06 \pm 0.06) \times 10^{-5}$ over the redshift range $0.4 < z < 2.3$ from a large sample of UVES data (see also [5]), the issue remains controversial and needs further investigation.

In any unified theory in which the gauge fields have a common origin, variations in the fine structure constant will be accompanied by similar variations in other gauge couplings [6]. It is therefore crucial to couple measurements of different dimensionless constants [7]. Although it is hard to make any quantitative prediction, theorists estimate that variations of the proton-to-electron mass ratio could be larger than that of the fine structure constant by a factor of 10–50 [8].

One way to constrain the cosmological variations of the proton-to-electron mass ratio is to measure the wavelengths of radiative transitions produced by the hydrogen molecule, H_2, at high redshift (i.e. in the early universe) and to compare them to those measured now in the laboratory on Earth. The method is based on the fact that wavelengths of electron-vibro-rotational lines depend on the reduced mass of the molecule, with the dependence being different for different transitions. It is therefore possible to distinguish the cosmological redshift of a line from the shift caused by a possible variation of μ. Thus, the measured wavelengths λ_i^{obs} of a line formed at redshift z_{abs} can be written as

$$\lambda_i^{obs} = \lambda_i^{lab}(1 + z_{abs})(1 + K_i \Delta\mu/\mu), \tag{1}$$

where λ_i^{lab} is the laboratory (vacuum) wavelength of the transition, and $K_i = (\mu/\lambda_i)(d\lambda_i/d\mu)$ is the sensitivity coefficient [9,10]. Previous studies have already yielded tight upper limits on the variation of μ of the order of $\delta\mu/\mu < 10^{-4}$ (see [11] and references therein). Here, we present a new measurement on an unprecedented large sample of 79 absorption lines, with simple profile structures, detected along two independent lines of sight.

2. Data

We used the UVES echelle spectrograph mounted on the Very Large Telescope of the European Southern Observatory to obtain new and better quality data (compared to what was available in the UVES data base) on two high-redshift ($z_{em} = 3.22$ and 3.02) bright quasars, respectively Q 0347–383 and Q 0405–443. Nine exposures of 1.5 h each were taken for each of the quasars over six nights under sub-arcsec seeing conditions in January 2002 and 2003 for Q 0347–383 and Q 0405–443, respectively. The slit was 0.8 arcsec wide resulting in a resolution of $R \sim 53\,000$ over the wavelength range 3290–4515 Å. Thorium–Argon calibration data were taken with different slit widths (from 0.8 to 1.4 arcsec) before and after each exposure and data reduction was performed using these different calibration settings to ensure accurate wavelength calibration. Spectra were extracted using procedures implemented in MIDAS, the ESO data reduction package. The reduction is particularly robust as only one CCD is used for the observations (setting #390). We have extracted the lamp spectra in the same way as the science spectra and checked that there is no systematic shift in the position of the emission lines.

Possible systematic effects leading to wavelength mis-calibration have been discussed by Murphy et al. [12] and we only specify here a few technical points. Wavelength calibration has been extensively checked using the ThAr lamps. Errors measured from the lamp spectra are typically $\sim$2 mÅ. Air-vacuum wavelength conversion has been made using Edlén [13] formula at 15°C. A shift in the wavelength scale can be introduced if the Thorium–Argon lamp and the experimental spectra are taken at systematically different temperatures. This is not the case here, as calibration spectra have been taken just before and after the experimental exposures. In any case, the temperature variations measured over one night in UVES are smaller than 0.5 K (see [14]). Heliocentric correction is made using the Stumpff [15] formula. In addition, all exposures have been taken with the slit aligned with the parallactic angle, so that atmospheric dispersion has little effect on our measurements. Therefore, as discussed by Murphy et al. [12], uncertainties due to these effects are neligible.

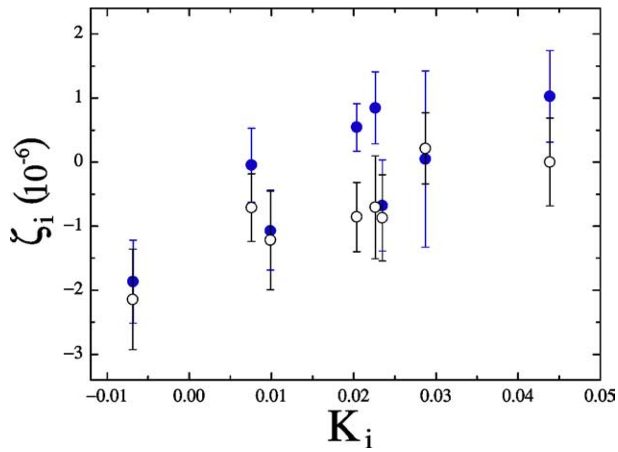

Fig. 1. The relative positions, $\zeta_i = (z_i - \bar{z})/(1 + \bar{z})$, of lines that are seen in the spectra of both quasars Q 0405–443 (filled circles) and Q 0347–383 (open circles) are plotted versus the sensitivity coefficient K_i. Here, $\bar{z}$ is the median redshift of all H_2 lines observed in one spectrum. The lines are L3R3, L3R2, L5R2, L6R3, L6P2, W0Q2, L8P3 and L12R3. The 1σ error bars shown are observational (without laboratory errors). They are of the order of 1 to 3 mÅ (in the observer's frame). It can be seen that both sets of measurements are mutually consistent within observational errors. The fact that the two independent observational measurements agree well suggests that our data calibration and measurement procedure are reliable at the level required for the study.

In each of the quasar spectra there is a damped Lyman-α system in which H_2 has been well studied, at $z_{abs} = 3.0249$ and 2.5947 for, respectively, Q 0347–383 and Q 0405–443 [16]. The unique advantage of these two systems is that numerous absorption lines with moderate optical depths are present. The line profiles are very simple: a single Gaussian component for Q 0347–383 and two well separated ($\Delta V = 13$ km s^{-1}) Gaussian components for Q 0405–443. For the latter system we only use the fits to the strongest component for measuring the variation in μ. The two quasars are therefore unique for such a measurement.

3. Consistency of the two lines of sight

We selected absorption lines that are not obviously blended with other lines (in particular intervening H I lines from the intergalactic medium) and have a central observed optical depth $0.1 < \exp(-\tau) < 0.9$. The 79 selected lines (39 in Q 0347–383 and 40 in Q 0405–443) were fitted with Gaussian profiles, estimating the continuum locally. Errors on the central wavelength are of the order of 1 to 3 mÅ. From the observed central wavelength, λ_i^{obs}, we calculate $(1 + z_i) = \lambda_i^{obs}/\lambda_i^{lab}$ where the laboratory wavelength, λ_i^{lab}, is estimated using level energies [17–20] determined from laboratory observations of the H_2 emission spectrum. Uncertainties for the ground state energies are less than 3×10^{-4} cm^{-1} [17]. Uncertainties are more difficult to estimate for the upper levels although close to 0.1 cm^{-1} for most of the lines [18]. This means that most of the errors in laboratory wavelengths should be of the same order of magnitude or slightly larger than our observational errors, 1 mÅ in the rest frame (or about 3 to 4 mÅ for the observer). It is, however, possible that some laboratory wavelengths are in error by larger amounts.

An important internal check of the data quality consists in comparing measurements of the eight lines present in both QSO spectra. This is shown in Fig. 1 where $\zeta_i = (z_i^{obs} - \bar{z})/(1 + \bar{z})$ is plotted versus K_i, $\bar{z}$ being the median redshift of all H_2 lines observed in one spectrum. It can be seen that all measurements are consistent within observational errors. As the two lines of sight have been observed and reduced independently, this shows that the data calibration and the measurement procedure are reliable at the level required for the study.

4. Results

In Fig. 2, we plot $\zeta_i = (z_i^{obs} - z_{abs})/(1 + z_{abs})$ versus K_i for 40 and 39 absorption lines observed in the spectra of, respectively, Q 0405–443 (filled circles) and Q 0347–383 (open circles). Here, z_{abs} is obtained from the best weighted linear fit of Eq. (1) to the data. We combined measurement errors (indicated as error bars) with a systematic error of 1 mÅ, in the rest frame, to account for uncertainties in laboratory wavelength determinations and wavelength calibration.

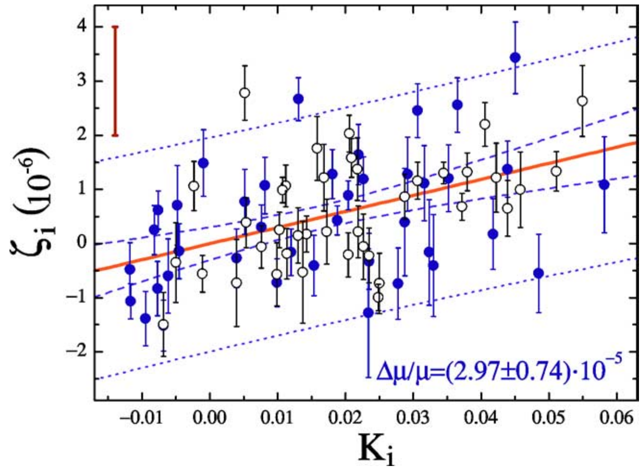

Fig. 2. The relative positions of absorption lines, $\zeta_i = (z_i^{obs} - z_{abs})/(1 + z_{abs})$, are plotted versus the sensitivity coefficient K_i for the 40 and 39 lines detected in the spectrum of, respectively, Q 0405–443 (filled circles) and Q 0347–383 (open circles). Here, z_{abs} is obtained from the best weighted linear fit of Eq. (1) to the data. We combined measurement errors (indicated as error bars) and a systematic error of 1 mÅ, in the rest frame, to account for uncertainty in laboratory wavelength determinations and the wavelength calibration. The mark on the left-hand side of the panel indicates the corresponding value of $\Delta\zeta_i$ calculated at 4000 Å. The linear weighted fit to the data is shown as a solid line. The long-dashed curves show the 95% confidence domain. The best fit is for $\Delta\mu/\mu = (2.97 \pm 0.74) \times 10^{-5}$. The short-dashed lines indicate the 95% prediction limits; only three absorption lines lie beyond these limits.

The best weighted linear fits to the data toward Q 0405–443 (40 lines) and Q 0347–383 (39 lines), give, respectively, $\Delta\mu/\mu = (3.00 \pm 0.97) \times 10^{-5}$ at $z_{abs} = 2.5947328$ and $\Delta\mu/\mu = (2.94 \pm 1.18) \times 10^{-5}$ at $z_{abs} = 3.0248992$. Combining the two sets of data gives $\Delta\mu/\mu = (2.97 \pm 0.74) \times 10^{-5}$ (indicated as a solid line in Fig. 2). Note that scatter in the data is of the same order of magnitude as the combined errors.

It has been shown, however, that absorption lines from different rotational J levels could be slightly shifted in velocity [21]. To take this possibility into account, we combined the lines using $\bar{z}$ calculated separately for each of the J levels. In the spectrum of Q 0405–443, there are 22 and 15 lines from, respectively, $J = 2$ and 3 levels whereas in the spectrum of Q 0347–383, there are 19, 9 and 11 lines from, respectively, $J = 1$, 2 and 3 levels. The calculated relative shifts between the mean positions of the different J levels are all very small, less than 0.4 $\mathrm{km\,s^{-1}}$. Using these shifts to correct for the mean position of the different J levels and combining the 76 lines together gives a best fit with $\Delta\mu/\mu = (2.67 \pm 0.78) \times 10^{-5}$ which is consistent with the previous result.

One may be concerned about the possibility that the complex internal structure of the cloud may induce some systematic effect. We have therefore performed a simultaneous and consistent two component fit of the 5 best-defined lines from the $J = 2$ level seen toward Q 0405–443 minimizing χ^2 with respect to the column density (N) and $\delta\mu/\mu$, keeping the Doppler parameter fixed, $b = 1.5$ $\mathrm{km\,s^{-1}}$. The minimization technique is described in Chand et al. [4]. We find a best fit for log $N(\mathrm{cm^{-2}}) = 15.8$ and 14.0 for the two components together with $\Delta\mu/\mu = (3.4 \pm 0.8) \times 10^{-5}$ which is consistent with the above result.

5. Conclusion

Using 79 H_2 absorption lines observed at $z_{abs} = 2.59473$ and 3.02490 in the spectra of two quasars, respectively, Q 0405–443 and Q 0347–383, we have shown that there is a correlation between the wavelength shifts of the lines measured as $\zeta_i = (z_i - z_{abs})/(1 + z_{abs})$ and the sensitivity coefficients K_i (see Eq. (1)). This can be interpreted as a variation of the proton-to-electron mass ratio, $\Delta\mu/\mu = (2.97 \pm 0.74) \times 10^{-5}$, over the past ∼ 12 Gyrs. This correlation is significant at more than the 3σ level even if we correct for possible velocity shifts between the positions of the absorption lines from different J levels. Errors in laboratory wavelengths are difficult to estimate, however, and although they are usually of the same order of magnitude as our observational errors, it is possible that for some of the lines, they are larger. If the true errors are larger than what we assumed, this will reduce the significance of the above noted correlation. In addition, as there is a well-known anticorrelation between K coefficients and rest-wavelengths of the lines, some hidden systematics might mimic the above result. It would be therefore of great interest to perform more precise laboratory measurements for the H_2 lines considered in this study. In addition, it would be very important to re-observe these same systems with a different instrument, and to search for more adequate systems where the measurement could be performed.

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