Constraining fundamental constants of physics with quasar absorption line systems

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Abstract. We summarize the attempts by our group and others to derive constraints on variations of fundamental constants over cosmic time using quasar absorption lines. Most upper limits reside in the range $0.5\times10^{-5}$ to $1.5\times10^{-5}$ at the $3\sigma$ level over a redshift range of approximately $0.5$ to $2.5$. It is therefore very important to perform new measurements to improve the sensitivity of the numerous methods to at least $0.1\times10^{-5}$ which should be possible in the next few years. Future instrumentations on ELTs in the optical and/or ALMA, EVLA and SKA pathfinders in the radio will undoubtedly boost this field by allowing to reach much better signal-to-noise ratios at higher spectral resolution and to perform measurements on molecules in the ISM of high redshift galaxies.

Keywords: Quasars: absorption lines; Physics: Fundamental constants

1. Introduction

As most of the successful physical theories rely on the constancy of few fundamental quantities (the speed of light, $c$, the fine-structure constant, $\alpha$, the proton-to-electron mass ratio, $\mu$, etc), constraining the possible time variations of these fundamental physical quantities is an important step toward understanding the rules of nature. Current laboratory constraints exclude any significant time variation of the dimensionless constants in the low-energy regime. It is not excluded however that they could have varied over cosmological timescales. Savedoff (1956) first pointed out the possibility of using redshifted atomic lines from distant objects to test the evolution of dimensionless physical constants. The idea is to compare the wavelengths of the same transitions measured in the laboratory on earth and in the remote universe. This basic principle has been first applied to QSO absorption lines by Bahcall et al. (1967). The field has been given tremendous interest recently with the advent of 10 m class telescopes.

For comparison with constraints obtained from laboratory experiments see other papers in this volume and reviews by others e.g. Uzan (2003) or Flambaum (2008).

2. The method

The idea is simply to compare wavelengths of the same transition measured in the remote universe and in the laboratory. As we live in an expanding universe we need at least two
transitions that have different sensitivities to the changes in fundamental constants. Ideally, transitions with no sensitivity to a variation of constants are used to measure the redshift and transitions with a large sensitivity to a variation of constants are used to constrain this variation once the redshift is known.

2.1. ATOMIC DATA

Modern spectrographs mounted on 10 m class telescopes provide high signal-to-noise ratio data on faint remote quasars at very high spectral resolution (typically $R \sim 50,000$). Since for a given spectral resolution, rest-frame measurements at high redshift have a better precision by a factor of 3 to 5 than laboratory determinations (see e.g. Petitjean & Aracil 2004), the method often requires dramatic improvements in laboratory measurements (see references in Murphy et al. 2003 for $\alpha$, Ubachs & Reinhold 2004, Philip et al. 2004, Ivanov et al. 2008 for $\mu$).

Atomic calculations are also needed to determine the sensitivity coefficients that characterize the change in rest wavelength due to a change in a given constant. This has been done for $\mu$ from $H_2$ lines (see Varshalovich & Potekhin 1995) and from molecular lines (e.g. Flambaum & Kozlov 2007) and for $\alpha$ (e.g. Dzuba et al. 2002 and references therein; Kozlov et al. 2008a,b)

2.2. QUasar ABSORPTION LINE SYSTEMS

The measurements are performed using absorption systems seen in the spectra of remote quasars. Fig. 1 shows a quasar spectrum obtained after a typical observation of 10 hours with UVES at the European Very Large Telescope. The quasar, at a redshift of $z_{em} = 2.58$, is quite bright and can be observed at high spectral resolution. Its spectrum is characterized by emission lines from the Lyman series of neutral hydrogen (Lyman-\(\alpha\), normally at 1215 Å is redshifted by a factor $1 + z_{em} = 3.58$ at $\sim 4340$ Å) or the resonance transitions from $C^{3+}$ (or C IV) normally at $\sim 1550$ Å and seen here at $\sim 5550$ Å. It can be seen that numerous absorption lines are superimposed on top of the continuum from the quasar. These absorptions arise when the line of sight crosses by chance a gaseous cloud. At wavelengths smaller than the Lyman-\(\alpha\) emission line from the quasar, any tiny amount of neutral hydrogen (corresponding to intergalactic clouds) will produce a narrow Lyman-\(\alpha\) absorption line. This region is called the Lyman-\(\alpha\) forest. Measurements try to avoid this region of the spectrum as any absorption can be blended with an intervening H I Lyman-\(\alpha\) line. This is not possible however for $H_2$ which UV lines are always redshifted in the Lyman-\(\alpha\) forest. When the line of sight passes through the halo or disk of a galaxy, a strong Lyman-\(\alpha\) absorption is seen together with metal lines. The strongest Lyman-\(\alpha\) lines (with column densities $\log N(H I) > 20.3$) correspond to the so-called damped Lyman-\(\alpha\) systems (see Fig. 1).

Small variations in the constants induce small positive or negative shifts in the wavelengths of atomic or molecular species. It must be realized that these shifts are quite small. For a relative variation of $\sim 10^{-5}$ in the fine-structure constant $\alpha$, the typical shift of transitions easily observable is $\sim 0.5$ km/s (the situation is slightly better in the radio, see below). This means about 20 mÅ for a redshift of about $z \sim 2$. This corresponds to about a third of a pixel at the spectral resolution of $R \sim 40000$ achieved with UVES-VLT or HIRES-Keck. This kind of measurement is not easy because (i) the number of independent absorption lines used in an individual measurement is not large, typically five or six, and (ii) several sources of uncertainties hamper the measurement.

The dependence of rest wavelengths to the variation of $\alpha$ is parameterized using the fitting function given by Dzuba et al. (1999), $\omega = \omega_0 + q_1 x + q_2 y$. Here $\omega_0$ and $\omega$ are, respectively, the vacuum wave number (in units of cm$^{-1}$) measured in the laboratory and
Figure 1. UVES-VLT spectrum of a quasar with emission redshift \( z_{\text{em}} = 2.58 \). The quasar is characterized by broad emission (H I Lyman-\( \alpha \) at \( \lambda \sim 4340 \, \text{Å} \), or C IV\( \lambda 1550 \) at \( \lambda \sim 4340 \, \text{Å} \)). Below 4350 Å, numerous H I Lyman-\( \alpha \) absorption lines are seen that are produced by intergalactic clouds (narrow lines) or galactic disks (the so-called "Damped Lyman-\( \alpha \) systems or DLAs) located by chance at smaller redshift along the line of sight to the quasar. A DLA system is present along this line of sight at \( z_{\text{abs}} = 2.33 \) (Lyman-\( \alpha \) absorption at \( \sim 4050 \, \text{Å} \)). Metal lines are seen above 4350 Å.

in the absorption system at redshift \( z \). \( x \) and \( y \) are dimensionless numbers defined as \( x = \left( \frac{\alpha_z}{\alpha_0} \right)^2 - 1 \) and \( y = \left( \frac{\alpha_z}{\alpha_0} \right)^4 - 1 \). The sensitivity coefficients \( q_1 \) and \( q_2 \) are obtained using many-body relativistic calculations (see Dzuba et al. 1999).

2.3. SOURCE OF ERRORS

The absorption lines have complex profiles because they are the result of the QSO photons travelling through the highly inhomogeneous medium that is associated with the potential wells of cosmological halos. These profiles are usually fitted using a combination of Voigt-profiles. For each component, the exact redshift, the column density and the width of the line (Doppler parameter) are fit parameters to be determined in addition to the shift from a possible variation of constants. These parameters are constrained assuming that the profiles are the same for all transitions. This is obviously true for transitions from the same species (as in Fig. 2) but is not necessarily true in case transitions from different species are used for the same measurement. Indeed, for testing the variations of \( \alpha_z \), transitions from Mg II, Si II and/or Fe II are commonly used. To avoid this problem, one could use transitions from one species only (Quast et al. 2004, Chand et al. 2005, Levshakov et al. 2006) but suitable systems are rare and the sensitivity of the method is reduced.
Figure 2. Fits of Si iv doublets. Absorption profiles are decomposed in Voigt-profile components (shown as dotted lines). Errors are increased in case the profile is strongly saturated. χ² curves are shown in the right-hand panels. Note that the SNR is particularly good in the present cases.

Another difficulty is that the fit is usually not unique. This is not a severe problem if the lines are not strongly saturated however (as in the bottom panel of Fig. 2) because in that case the positions of the components are well defined. Simulations have shown (Chand et al. 2004) that the presence of strongly saturated lines can increase errors on the determination of Δα/α by a factor of two in the case of a simple profile.

Spectra in the optical are taken with high resolution echelle spectrographs that have usually a red and a blue arm. In each arm the spectrum is split into a large number of orders and recorded on different CCDs. The wavelength calibration solution is calculated for each CCD. This can introduce local deviations from the correct solution that may be difficult to control. Wavelength calibration is of high importance here and should be carefully controlled (see Thompson et al. 2008 in the case of UVES). A way to overcome the difficulty is to use completely independent instruments to observe the same object. Chand et al. (2005) used the very stable spectrograph HARPS mounted on the 3.6 m telescope at the La Silla observatory to observe the bright quasar HE 0515−4414 that was previously observed with UVES. They find that although the dispersion of the wavelength solution is much smaller for HARPS than for UVES, errors are well constrained except for local artifacts. This means that even though wavelength calibration is not a concern at the sensitivity level we can expect to achieve, local problems can spoil the measurement for a few systems. Also for some methods, two absorptions lines in very different wavelength bands (e.g. the radio and the UV) are used (see Section 5.1) and the intercalibration has to be checked carefully.
Note that temperature must be controlled precisely or registered carefully so that adequate air-vacuum correction can be applied. Flexures in the instrument are dealt with by recording a calibration lamp spectrum before and after the science exposure which is usually 1 hour long. The signal-to-noise ratio of the data is a crucial issue. Simulations by Chand et al. (2004) showed that errors are inversely correlated with SNR. A minimum of SNR $\sim 50$ at the position of the absorption lines is required to achieve measurements at the level considered here.

3. Variation of the fine-structure constant $\alpha$

3.1. The Many-Multiplet Method

The power of the Many-Multiplet Method (MMM) is to use a large number of transitions to constrain the variation of $\alpha$. At least five transitions are used, usually from different species. The transitions are chosen so that their sensitivities to a change in $\alpha$ are different. For example, rest wavelengths of Mg II doublets and Mg I are fairly insensitive to small changes in $\alpha$ thereby providing good anchors for measuring the systemic redshift. Whereas the rest wavelengths of Fe II multiplets are very sensitive to small variations in $\alpha$. The accuracy depends on how well the absorption line profiles are modeled. The recent application of the many-multiplet method (Dzuba et al. 1999, Webb et al. 1999) has improved by an order of magnitude the accuracy of the $\Delta\alpha/\alpha$ measurements based on QSO absorption lines (Webb et al. 2001). Analysis of HIRES/Keck data has resulted in the claim of a variation in $\alpha$, $\Delta\alpha/\alpha = (-0.54 \pm 0.12) \times 10^{-5}$, over a redshift range $0.2 < z < 3.7$ (Murphy et al. 2003).

In order to check this result independently, we have applied the MM method to very high quality (SNR $\sim 60 - 80$, $R \geq 44,000$) UVES/VLT data. In view of the numerous systematic errors involved in the MM method, we have carried out detailed simulations to define proper selection criteria to choose suitable absorption systems in order to perform the best analysis (see Chand et al. 2004 for details). Application of these selection criteria to the full sample of 50 Mg II/Fe II systems lead us to restrict the study to 23 Mg II/Fe II systems over a redshift range $0.4 \leq z \leq 2.3$. The weighted mean of the individual measurements from this analysis is a non-detection with a 3$\sigma$ upper limit of $\Delta\alpha/\alpha < 0.20 \times 10^{-5}$ (Srianand et al. 2004, Chand et al. 2004).

All further analysis performed with UVES spectra fail to confirm any variation in $\alpha$ (Quast et al. 2004; Lezhakov et al. 2005). In particular, Chand et al. (2006) analyse spectra of the bright quasar HE 0515-4414 taken with two different instruments, UVES at the VLT and HARPS at the 3.6 m telescope in La Silla. They show that the results of a non-evolving $\alpha$ reported in the literature based on UVES/VLT data should not be heavily influenced by problems related to wavelength calibration uncertainties and multiple component Voigt profile decomposition. Considering that different procedures can be used, a robust 3$\sigma$ limit on the variation of $\alpha$ at $z \sim 1.5$ obtained with UVES data is $\Delta\alpha/\alpha < 0.30 \times 10^{-5}$.

Note that several authors have used the five transitions of Fe II to obtained a limit from absorption lines of only one species in order to be certain that the profile structures are identical (Quast et al. 2004, Chand et al. 2006, Lezhakov et al. 2007). Useful atomic data are given by Porsev et al. (2007). The number of systems suitable for such measurements is unfortunately very small and limits achieved are of the same order of magnitude.

It is now of high importance to improve the procedure and to increase the number of measurements in order to decrease this limit to below $10^{-6}$ which is a reasonable goal for present day instrumentation.
3.2. THE ALKALI DOUBLET (AD) METHOD

Alkali doublets are conspicuous in astrophysical spectra both in emission (for example the [O III]λλ4969,5007 doublet) and in absorption (for example the Si IVλ1393,1402 or the C IVλλ1548,1550 doublets). In the later case however atomic data are not well known (e.g. Petitjean & Aracil 2004). The method, although less sensitive than the MM method, has the advantage to use only one species and to be applicable to higher redshifts. Bahcall et al. (1967) were the first of a long list to apply this technique to QSO spectra.

More recently, Murphy et al. (2001) analysed a KECK/HIRES sample of 21 Si IV doublets observed along 8 QSO sight lines and derived $\Delta \alpha / \alpha < 3.9 \times 10^{-5}$. The analysis of 15 Si IV doublets selected from a ESO-UVES sample yielded the strongest constraint obtained with this method: $\Delta \alpha / \alpha < 1.3 \times 10^{-5}$ over the redshift range $1.59 \leq z \leq 2.92$ (Chand et al. 2005).

The AD method can be applied to emission as well as absorption lines. However emission lines are usually broad as compared to absorption lines. Errors are therefore larger on individual measurements and must be beaten by large statistics. As a result, the constraints obtained from emission lines are not as strong as those derived from absorption lines. Bahcall et al. (2004) have recently found $\Delta \alpha / \alpha < 4.2 \times 10^{-4}$ using O III emission lines from SDSS QSOs.

4. Variation of the proton-to-electron mass ratio $\mu$

In the framework of unified theories (e.g. SUSY GUT) with a common origin of the gauge fields, variations of the gauge coupling $\alpha_{\text{GUT}}$ at the unified scale ($\sim 10^{16}$ GeV) will induce variations of all the gauge couplings in the low energy limit, $\alpha_i = f_i(\alpha_{\text{GUT}}, E)$, and provide a relation $\Delta \mu / \mu \approx R \Delta \alpha / \alpha$, where $R$ is a model dependent parameter and $|R| \leq 50$ (e.g. Dine et al. 2003, and references therein). Thus, independent estimates of $\Delta \alpha / \alpha$ and $\Delta \mu / \mu$ could constrain the mass formation mechanisms in the context of unified theories.

On earth, the proton-to-electron mass ratio has been measured with a relative accuracy of $2 \times 10^{-9}$ and equals $\mu_0 = 1836.15267261(85)$. Laboratory metrological measurements rule out considerable variation of $\mu$ on a short time scale but do not exclude its changes over the cosmological scale, $\sim 10^{10}$ years. Moreover, one can not reject the possibility that $\mu$ (as well as other constants) could be different in widely separated regions of the Universe.

4.1. $\text{H}_2$

The method using $\text{H}_2$ transitions to constrain the possible variations of $\mu$ was proposed by Varshalovich and Levshakov (1993). It 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 enables us to distinguish the cosmological redshift of a line from the shift caused by a possible variation of $\mu$.

Thus, the measured wavelength $\lambda_i$ of a line formed in the absorption system at the redshift $z_{\text{abs}}$ can be written as, $\lambda_i = \lambda_i^0 (1 + z_{\text{abs}})(1 + K_i \Delta \mu / \mu)$, where $\lambda_i^0$ is the laboratory (vacuum) wavelength of the transition, and $K_i = d \ln \lambda_i / d \ln \mu$ is the sensitivity coefficient for the Lyman and Werner bands of molecular hydrogen (Varshalovich and Potekhin 1995). This expression can be represented in terms of the individual line redshift $z_i \equiv \lambda_i / \lambda_i^0 - 1$ as, $z_i = z_{\text{abs}} + b K_i$, where $b = (1 + z_{\text{abs}}) \Delta \mu / \mu$.

In reality, $z_i$ is measured with some uncertainty which is caused by statistical errors of the astronomical measurements, $\lambda_i$, and by errors of the laboratory measurements of $\lambda_i^0$. Nevertheless, if $\Delta \mu / \mu$ is nonzero, there must be a correlation between $z_i$ and $K_i$. 

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values. Thus, a linear regression analysis of these quantities yields \( z_{\text{abs}} \) and \( b \) (as well as its statistical significance), consequently an estimate of \( \Delta \mu/\mu \).

Several studies have yielded tight upper limits on \( \mu \)-variations, \( |\Delta \mu/\mu| < 7 \times 10^{-4} \) (Cowie & Songaila 1995), \( |\Delta \mu/\mu| < 2 \times 10^{-4} \) (Potekhin et al. 1998), \( |\Delta \mu/\mu| < 5.7 \times 10^{-5} \) (Levshakov et al. 2002) and \( \Delta \mu/\mu < 7 \times 10^{-5} \) (Ivanchik et al. 2003). Recently, a new limit was estimated, \( \Delta \mu/\mu < 2.2 \times 10^{-5} \) at the 3\( \sigma \) level, by measuring wavelengths of 76 \( \text{H}_2 \) lines of Lyman and Werner bands from two absorption systems at \( z_{\text{abs}} = 2.5947 \) and 3.0249 in the spectra of quasars Q 0405−443 and Q 0347−383, respectively. Data were of the highest spectral resolution (\( R = 53000 \)) and S/N ratio (30–70) for these kind of studies (Ivanchik et al. 2005).

This result is subject to important systematic errors of two kinds: (i) using different sets of laboratory wavelengths yield different results; (ii) the molecular lines are located in the Lyman-\( \alpha \) forest where they can be strongly blended with intervening \( \text{H}_1 \) Lyman-\( \alpha \)-absorption lines. The first type of systematics are addressed by new laboratory measurements (Philip et al. 2005; Reinhold et al. 2006). The second type of systematics needs careful fitting of the Lyman-\( \alpha \) forest. This has been performed recently by King et al. (2008). These authors use principally the same set of data as above and derive \( \Delta \mu/\mu < 1.2 \times 10^{-5} \) at the 3\( \sigma \) level.

4.2. HD

The detection of several HD transitions makes it possible to test the possible time variation of the proton-to-electron mass ratio, in the same way as with \( \text{H}_2 \) but in a completely independent way. As these measurements may involve various unknown systematics, it is important to use different sets of lines and different techniques. Sensitivity coefficients and accurate wavelengths for HD transitions have been published very recently (Ivanov et al. 2008). It must be noted however that till now \( \text{H}_2 \) is detected in absorption in only 14 Damped Lyman-\( \alpha \) systems whereas HD is detected in only two places in the whole universe.

Deuterated molecular hydrogen was detected very recently together with carbon monoxide (CO; Srianand et al. 2008) and \( \text{H}_2 \) in a Damped Lyman-\( \alpha \) cloud at \( z_{\text{abs}} = 2.418 \) toward the quasar SDSS1439+11. Five lines of HD in three components were detected together with more than a hundred \( \text{H}_2 \) transitions in seven components. Although each HD component is associated to one of the \( \text{H}_2 \) components, the strong blending of the latter, especially in low rotational levels, does not allow for the exact determination of the relative positions of the HD and \( \text{H}_2 \) components. In passing, the column densities integrated over the whole profile for both HD and \( \text{H}_2 \) yield \( \mathcal{N}(\text{HD})/2\mathcal{N}(\text{H}_2) = 1.5^{+0.6}_{-0.4} \times 10^{-5} \) (Noterdaeme et al. 2008). Five HD absorption lines (L3-0 R0, L5-0 R0, L7-0 R0, L8-0 R0 and W0-0 R0) are clearly detected and were fitted simultaneously. The 3\( \sigma \) limit reached here is \( \Delta \mu/\mu < 9 \times 10^{-5} \).

Although the number of available lines and the signal-to-noise ratio do not allow to reach the level of accuracy achieved with \( \text{H}_2 \), it is important to pursue in this direction and to measure \( \Delta \mu/\mu \) also from HD lines. This is very important given the scarcity of possible independent measurements.

4.3. \( \text{NH}_3 \)

Recently, Flambaum & Kozlov (2007) showed that the high sensitivity of the \( \text{NH}_3 \) inversion transitions to a change in \( \mu \) could be used to constrain the variations of this constant. The only intermediate redshift system where this molecule is detected is the \( z = 0.685 \) lens toward B 0218+357 (Combes & Wiklind 1995, Henkel et al. 2005). They obtain a 3\( \sigma \) upper limit on the variation of \( \mu \) at this redshift of \( 6 \times 10^{-6} \). Murphy et al. (2008) refined this limit.
5. Combinations of constants

5.1. THE 21 CM ABSORBERS

As the energy of the hyperfine H I 21-cm transition is proportional to the combination of three fundamental constants, \( x = \alpha^2 g_p / \mu \), high resolution optical and 21-cm spectra can be used together to probe the combined cosmological variation of these constants (Tubbs & Wolfe 1980). In the definition of \( x \), \( \alpha \) is the fine-structure constant, \( \mu \) is the proton-to-electron mass ratio and \( g_p \) is the gyromagnetic factor (dimensionless) of the proton (see e.g. Tzanavaris et al. 2005).

To apply this technique, the redshift of the 21 cm line must be compared to that of UV lines of Si II, Fe II and/or Mg II. Two difficulties arise: (i) the radio and optical sources must coincide: as QSOs in the optical can be considered as pointlike sources, it must be checked on VLBI maps that the corresponding radio source is also pointlike which is not true for all quasars; (ii) the gas at the origin of the 21 cm and UV absorptions must be co-spatial: it is likely to be the case if the lines are narrow. Therefore systems in which the measurement can be performed must be selected carefully. Since the overall number of suitable systems is very small, they must be searched for.

For this reason we have embarked on a large survey to search for 21 cm absorbers at intermediate and high redshifts. For this we first selected strong Mg II systems (\( W_r > 1 \AA \)) from the Sloan Digital Sky Survey in the redshift range suitable for a follow-up with the Giant Meterwave Telescope (GMRT), \( 1.10 < z_{\text{abs}} < 1.45 \). We then cross-correlated the \( \sim 3000 \) SDSS systems we found with the FIRST radio survey to select the background sources having at least a \( S_{1.4\text{GHz}} > 50 \) mJy bright component coincident with the optical QSO. There are only 63 sources fulfilling these criteria out of which we observed 35 over \( \sim 400 \) hours of GMRT observing time.

We detected 9 new 21 cm absorption systems. This is by far the largest number of 21-cm detections from any single survey. Prior to our survey no intervening 21-cm system was known in the above redshift range and only one system was known in the redshift range \( 0.7 \leq z \leq 1.5 \). Our GMRT survey thus provides systems in a narrow redshift range where variations of \( x \) can be constrained. For this, high resolution and high signal-to-noise ratio observations of the absorbers must be performed to detect the UV absorption lines that will provide the anchor to fix the exact redshift, the variations of \( x \) being then constrained by the position of the 21 cm absorption line.

These UV observations exist for one of the system at \( z_{\text{abs}} = 1.3608 \) (see Fig. 3). Although the UV data could be even better, a preliminary constraint was obtained: \( \Delta x/x < 10^{-5} \) at the 3 \( \sigma \) level.

5.2. OTHER MOLECULES: CO, OH, NH\(_3\), HCO\(^+\)

Other molecules can be used to derive strong constraints on fundamental constants. Wiklind & Combes (1999) noticed that a potential application of the observation of radio molecular absorption lines at high redshift is to check the invariance of constants. Radio lines are well suited for this purpose because spectral resolution better than 1 km s\(^{-1}\) can be achieved in the radio wavelength range. By comparing the redshift of a molecular transition to that of the 21 cm hyperfine H I line, it is possible to constrain a combination \( \alpha^2 g_p (M_{\text{red}}/m_p) \) of the proton gyromagnetic ratio \( g_p \), \( \alpha \) and the ratio of the reduced mass of the molecule to the proton mass. They already put a 3\( \sigma \) limit of \( 10^{-5} \) on the variations of the above coefficient.
Figure 3. Detection of 21 cm absorption in a cloud at $z_{\text{abs}} = 1.3608$. The 21 cm component is very narrow and is associated with a UV component well detached from the bulk of the Si II absorption profile. A comparison of the positions of these two transitions sets strong constraints on the parameter $\alpha^2 g_p/\mu$. It is apparent that the errors will come from the determination of the position of the UV Si II absorption line.

Similarly, beautiful observations of conjugate absorption and emission OH lines have been performed recently. Kanekar et al. (2005) have detected the four 18 cm OH lines from the $z_{\text{abs}} = 0.765$ gravitational lens toward PMN J0134−0931 with the 1612 and 1720 MHz lines in conjugate absorption and emission (see also Kanekar & Chengalur 2004). They compare the HI and OH absorption redshifts of the different components in this system and also in the absorber arising from the $z = 0.685$ lens toward B 0218+357 to place stringent constraints on changes in $F = g_p(\alpha^2/\mu)^{1.57}$. They obtain $\Delta F/F < 4 \times 10^{-5}$.
Table I. Constraints on the cosmological variations of fundamental constants

| Method | Redshift | Constraint (10^{-5})^a | References^b |
|--------|----------|-------------------------|---------------|
| $\alpha$ | MMM | 0.2 – 3.7 | $-0.54\pm0.12$ | Murphy et al. (2003) |
| | | 0.5 – 2.5 | $<0.30$ | Srianand et al. (2004) |
| FeII | 1.515 | | $<0.45$ | Quast et al. (2004), Levshakov et al. (2005) |
| AD (SiIV) | 1.6 – 2.8 | | $<1.3$ | Chand et al. (2005) |
| AD ([OIII]) | 0.15 – 0.8 | | $<42$ | Bahcall et al. (2004) |
| $\mu$ | H$_2$ | 2.595, 3.025 | <2.1 | Ivanchik et al. (2005), Reinhold et al. (2006) |
| | | 2.595, 3.025 | <1.2 | King et al. (2008) |
| | HD | 2.418 | <9 | Noterdaeme et al. (2008) |
| | NH$_3$ | 0.685 | <0.27 | Flambaum & Kozlov (2007), Murphy et al. (2008) |
| | 21cm | 1.361 | <1.0 | Srianand et al. (2009) |
| | OH | 0.685 | <4.0 | Kanekar et al. (2005) |
| | NH$_3$ | 0.685 | <5.0 | Flambaum & Kozlov (2007) |
| | CO, HCO$^+$ | 0.25, 0.685 | <1.0 | Wiklind & Combes (1997) |

^a 3$\sigma$ for upper limits; ^b See Text for other references.

6. Conclusion

Results are summarized in Table I. Column #1 gives the constant under study (see definitions in the Text above), #2 is for the method used, #3 indicates the redshift at or the redshift range over which the measurement is performed, #4 gives the constraints or measurement obtained and #5 gives partial references (other references are given in the Text above). It is apparent that constraints reside in the range $\sim 0.3–1.5 \times 10^{-5}$ at the 3$\sigma$ level over a redshift range of approximately 0.5 – 2.5. Note that Reinhold et al. (2006) do not claim detection. They are cautious enough to state that systematics dominate the measurements. Indeed, data and observed wavelength determinations are the same as those in Ivanchik et al. (2005). The only claimed detection of varying $\alpha$ is from Murphy et al. (2003). It is therefore very important to increase the number of measurements and to improve the measurements themselves (e.g. Thompson et al. 2008) to reach the sensitivity level of at least $<0.1 \times 10^{-5}$ which should be possible in the next few years. Future instrumentation on ELTs will undoubtedly boost this field by allowing to reach much better signal-to-noise ratios at higher spectral resolution (e.g. Liske et al. 2008). As discussed above, the strongest constraints may come from radio observations of molecules in the ISM of high redshift galaxies. A new area will be opened in this field by the upcoming facilities such as ALMA and EVLA for high-redshift molecular studies and SKA pathfinders for 21 cm and OH surveys.

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