Constraining the variation of fundamental constants at $z \sim 1.3$ using 21-cm absorbers

H. Rahmani, 1† R. Srianand, 1 N. Gupta, 2 P. Petitjean, 3 P. Noterdaeme 3 and D. Albornoz Vásquez 3

1 Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India
2 Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA, Dwingeloo, the Netherlands
3 Institut d’Astrophysique de Paris, CNRS-UMR7095, Université Pierre et Marie Curie, 98bis Boulevard Arago, 75014 Paris, France

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ABSTRACT

We present high-resolution optical spectra obtained with the Ultraviolet and Visual Echelle Spectrograph at the Very Large Telescope and 21-cm absorption spectra obtained with the Giant Metrewave Radio Telescope and the Green Bank Telescope of five quasars along the line of sight of which 21-cm absorption systems at $1.17 < z < 1.56$ have been detected previously. We also present milliarcsecond-scale radio images of these quasars obtained with the Very Large Baseline Array. We use the data on four of these systems to constrain the time variation of $\delta x/x$, where $g_p$ is the proton gyromagnetic factor, $\alpha$ is the fine structure constant and $\mu$ is the proton-to-electron mass ratio. We carefully evaluate the systematic uncertainties in redshift measurements using cross-correlation analysis and repeated Voigt profile fitting. In both cases, we also confirm our results by analysing optical spectra obtained with the Keck telescope. We find the weighted and the simple means of $\Delta x/x$ to be, respectively, $-(0.1 \pm 1.3) \times 10^{-6}$ and $0.0 \pm 1.5 \times 10^{-6}$ at the mean redshift of $z = 1.36$ corresponding to a look-back time of $\sim 9$ Gyr. This is the most stringent constraint ever obtained on $\Delta x/x$. If we only use the two systems towards quasars unresolved at milliarcsecond scales, we get the simple mean of $\Delta x/x = +(0.2 \pm 1.6) \times 10^{-6}$. Assuming the constancy of other constants, we get $\Delta \alpha / \alpha = (0.0 \pm 0.8) \times 10^{-6}$, which is a factor of 2 better than the best constraints obtained so far using the many-multiplet method. On the other hand, assuming that $\alpha$ and $g_p$ have not varied we derive $\Delta \mu / \mu = (0.0 \pm 1.5) \times 10^{-6}$ which is again the best limit ever obtained on the variation of $\mu$ over this redshift range. Using independent constraints on $\Delta \alpha / \alpha$ at $z < 1.8$ and $\Delta \mu / \mu$ at $z \sim 0.7$ available in the literature, we get $\Delta g_p / g_p \leq 3.5 \times 10^{-6} (1\sigma)$. 

Key words: quasars: absorption lines – quasars: individual: J0108−0037 – quasars: individual: J0501−0159 – quasars: individual: J1623+0718 – quasars: individual: J2340−0053 – quasars: individual: J2358−1020.

1 INTRODUCTION

Most of the successful physical theories rely on the constancy of a few fundamental quantities such as the fine structure constant, $\alpha = e^2/\hbar c$, the proton-to-electron mass ratio, $\mu$, etc. Some modern theories of high-energy physics that try to unify the fundamental interactions predict the variation of these dimensionless fundamental constants over cosmological scales (see Uzan 2003, and references therein for more details). Current laboratory constraints exclude any significant variation of these constants over Solar system scales and on geological time-scales (see Olive & Skillman 2004; Petrov et al. 2006; Rosenband et al. 2008). It is not observationally/experimentally excluded, however, that they could vary over cosmological scales. Therefore, constraining time and spatial variations of fundamental constants of physics will have a great impact on understanding the true behaviour of the nature.

Savedoff (1956) first pointed out the possibility of using redshifted atomic lines from distant objects to test the evolution of dimensionless physical constants. Initial attempts in this field mainly used the alkali-doublet (AD) method to constrain $\alpha$ variation (Savedoff 1956; Bahcall & Schmidt 1967; Wolfe, Brown...
& Roberts 1976; Levshakov 1994; Cowie & Songaila 1995; Varshalovich, Panchuk & Ivanchik 1996; Varshalovich, Potekhin & Ivanchik 2000; Murphy et al. 2001; Chand et al. 2005). While the AD method is simple and least affected by systematics related to ionization and chemical inhomogeneities, the limits achieved on $\Delta x/\alpha = (\alpha - \alpha_0/\alpha_0$ are not usually stringent. The most precise value reported to date using this method is $\Delta x/\alpha = -(0.02 \pm 0.55) \times 10^{-3}$ (Chand et al. 2005) over a redshift range of $1.59 \leq z \leq 3.7$.

Dzuba, Flambaum & Webb (1999a,b) and Webb et al. (1999) introduced the many-multiplet (MM) method as a generalization of the AD method, in which one correlates different multiplets from different ions simultaneously. Applying this method on a sample of 128 absorbers observed at high spectral resolution with the Keck telescope, Murphy, Webb & Flambaum (2003) claimed a detection, $\Delta x/\alpha = -(0.57 \pm 0.10) \times 10^{-3}$, over the redshift range $0.2 \leq z \leq 3.7$. However, this result was not confirmed by Srianand et al. (2004) and Chand et al. (2004) who used higher signal-to-noise ratio (SNR $\sim$ 70 per pixel) and high-spectral-resolution ($R \geq 45000$) Ultraviolet and Visual Echelle Spectrograph/Very Large Telescope (UVES/VLT) data of 23 Mg II systems detected towards 18 quasars in the redshift range $0.4 \leq z \leq 2.3$ and found $\Delta x/\alpha = -(0.06 \pm 0.06) \times 10^{-5}$. This analysis was criticized by Murphy, Webb & Flambaum (2007). However, from the reanalysis of the UVES data, using the Voigt profile fitting code VPFIT, Srianand et al. (2007) confirmed the null result albeit with larger error bars [i.e. $\Delta x/\alpha = (0.01 \pm 0.15) \times 10^{-3}$]. Other analysis using only Fe II transitions in two particularly well-suited absorption systems at $z = 1.15$ and $1.84$ failed to confirm any variation in $\alpha$ (Quast, Reimers & Levshakov 2004; Chand et al. 2006; Levshakov et al. 2006, 2007). Recently, Webb et al. (2011) have reported the results of the analysis of 153 systems present in quasar spectra observed with VLT/UVES. They find that $\alpha$ increases with increasing cosmological distance from the Earth. Moreover for $z < 1.8$, they confirm the results given by Srianand et al. (2007), $\Delta x/\alpha = -(0.6 \pm 1.6) \times 10^{-6}$. However, combining their new VLT measurements with their previous Keck measurements, they suggest the possibility for a spatial variation of $\alpha$ and speculate on the existence of an $\alpha$ dipole. If true, this dipole is very difficult to explain theoretically (Olive, Peloso & Uzan 2011). While the MM method provides improved precision, it is affected by systematics related to ionization, chemical inhomogeneities and isotopic composition. The effects of inhomogeneities can be cancelled using a large sample of absorption systems, but the effects of isotopic composition will likely to remain an issue.

Most of the existing theories predict that the proton-to-electron mass ratio $\mu$ should vary much more than $\alpha$ (for example, see Olive et al. 2002; Dent & Fairbairn 2003; Dine et al. 2003, and references therein) though some predict the reverse (Dent, Stern & Wetterich 2008). The variations of $\mu$ can be probed using H$_2$ Lyman- and Werner-band absorption lines (Varshalovich & Levshakov 1993). H$_2$ molecules are occasionally detected in high-redshift damped Lyman $\alpha$ systems (Petitjean, Srianand & Ledoux 2000; Ledoux, Petitjean & Srianand 2003; Noterdaeme et al. 2008; Srianand et al. 2012) with only a handful of them being suitable for probing the variation of $\mu$. No clear indication of any variation in $\mu$ in excess of one part in $10^3$ is seen in the existing data for $z \geq 2$ (Ivanchik et al. 2005; Reinhold et al. 2006; King et al. 2008; Thompson et al. 2009; van Weerenburg et al. 2011; Wendt & Molaro 2011). By comparing the inversion line transitions of NH$_3$ with the rotational transitions of other molecules, a strong constraint on $\Delta \mu/\mu$ can be obtained (Murphy et al. 2008). At present, such an exercise is possible for only two gravitationally lensed systems at $z < 1$ (Henkel et al. 2005, 2008). The best reported constraint is $\Delta \mu/\mu \leq 3.6 \times 10^{-3}$ (3$\sigma$) at $z = 0.685$ by Kanekar (2011). Detecting more NH$_3$ absorption towards normal quasars is required to reduce systematics related to the usage of lensed quasars (see Henkel et al. 2008 for discussions on various other systematics).

As the energy of the 21-cm transition is proportional to $x \equiv \alpha^2 3p/\mu$, high-resolution optical spectra and 21-cm spectra can be used together to probe the combined variation of these constants (Wolfle et al. 1976). Constraints of the order of $\sigma(\Delta x/\alpha) \leq 10^{-5}$ were obtained towards individual systems (Cowie & Songaila 1995; Kanekar et al. 2006; Srianand et al. 2010). Tzanavaris et al. (2007) derived $\Delta x/\alpha = (0.63 \pm 0.99) \times 10^{-3}$ for a sample of nine 21-cm absorbers with $0.23 < z < 2.35$. The majority of the 21-cm spectra used in this study were digitally scanned from the printed literature and the ultraviolet (UV)–data optical were obtained mainly with VLT/UVES. Better constraints can be derived from higher quality spectra in the radio and optical wavelength ranges of a well-selected sample of 21-cm absorbers. This is possible now thanks to systematic surveys for 21-cm absorption towards strong Mg II absorbers (e.g. Gupta et al. 2009). This work has resulted in the detection of nine new 21-cm absorption systems over a narrow redshift range (i.e. $1.05 \leq z \leq 1.45$) that can be used for constraining $\Delta x/\alpha$.

While this technique is very powerful, there are two issues that introduce systematic uncertainties in the measurements. These are (i) the identification of the optical component corresponding to the gas that produces the 21-cm absorption and (ii) the fact that the radio and optical sources could probe different volumes of the absorbing gas as the radio-emitting region in quasars is in general extended compared to the UV-emitting region. It has been suggested that the gas detected by their C I and/or H$_2$ absorption is closely associated with the 21-cm gas (Cowie & Songaila 1995; Srianand et al. 2010). However, only few 21-cm absorbers show detectable C I and H$_2$ absorption, and even in these cases velocity offsets up to 1–2 km s$^{-1}$ are noticed (Srianand et al. 2012). All these indicate that C/H$_2$ and 21-cm absorption need not originate from the same physical region. Another option is to connect 21-cm absorption to absorption from singly ionized species that trace H I gas. For example, Tzanavaris et al. (2007) have associated the pixel with the strongest absorption in the UV with the pixel with the strongest 21-cm absorption. As neighbouring pixels are correlated in optical spectra, the redshift of the strongest metal absorption component will be better defined by using simultaneous Voigt profile fits to the absorption lines. This is the method we adopt in the analysis presented here. The second uncertainty discussed above can be minimized by selecting absorbers towards quasars that are compact at milliarcsecond scales. While individual measurements may not be completely free of these systematics, even after careful consideration of the specific properties of the system, it should be possible to minimize them and get a statistically reliable measurement using a large sample of absorbers.

As different methods used for constraining the fundamental constants suffer from different systematic effects, it is important to increase the number of measurements based on each method to address the time and space variation of different constants. Here we provide new measurements of $\Delta x/\alpha$ using a new sample of 21-cm absorbers.

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1 Here $\alpha_0$ and $\alpha_0$ are the measured values of $\alpha$ at any redshift, $z$, and in the laboratory on the Earth.

2 http://www.ast.cam.ac.uk/rfc/vpfit.html

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We have selected five systems from the literature [four from Gupta et al. (2009) and one from Kanekar et al. (2009)] previously known to be associated with narrow 21-cm absorption lines towards radio sources that are compact at arcsecond scales. We have obtained high-resolution UV and radio data of the quasars together with high-resolution Very Large Baseline Array (VLBA) images. We report here the analysis of this data set. This paper is organized as follows. In Section 2, we present details of optical and radio observations and data reduction. In Sections 3 and 4, we provide details of Gaussian fits to the 21-cm absorption lines and Voigt profile fitting of the UV lines. In Section 5, we summarize our Δλ/σ measurements in individual systems and discuss the associated systematic errors. In Section 6, we discuss the results and conclude. We use simultaneous Voigt profile fits to identify the redshift of the strongest UV component closest to the 21-cm absorption. We also discuss the results when we adopt the method used by Tzanavaris et al. (2007).

2 OBSERVATIONS AND DATA REDUCTION

2.1 Optical spectroscopy

The optical spectroscopic observations of quasars were carried out with UVES (Dekker et al. 2000) at the VLT UT2 8.2-m telescope at Paranal (Chile) in service mode (Programmes 082.A-0569A and 085.A-0258A). All observations were performed using the standard beam splitter with the dichroic #2 (setting 390+580) that covers roughly from 330 to 450 nm on the BLUE CCD and from 465 to 578 nm and 583 to 680 nm on the two RED CCDs. Slit width of 1 arcsec and CCD readout with 2 × 2 binning were used for all the observations resulting in a pixel size of \( \approx 1.7 \) km s\(^{-1}\) and spectral resolution of \( \approx 45,000 \). D’Odorico et al. (2000) have shown that the resetting of the gratings between an object exposure and the ThAr calibration lamp exposure can result in an error of the order of a few hundred metres per second in the wavelength calibration. To minimize this effect, each science exposure was followed immediately by an attached set of five ThAr lamp exposures. In the case of J0501−0159, we have retrieved all the UVES data available in the European Southern Observatory archive. As these spectra were not acquired specifically for constraining the variation of fundamental constants, there is no attached calibration lamp exposure taken along with the science observations. However, these data were reduced using the available lamp spectra closest in time.

These data were reduced with the UVES Common Pipeline Library data reduction pipeline release 4.7.8\(^3\) using the optimal extraction method. We used fourth-order polynomials to find the dispersion solution. The number of suitable ThAr lines used for wavelength calibration was always larger than 400, and the rms error was found to be in the range 70–80 m s\(^{-1}\) with zero average. However, this error applies only to regions very close to the ThAr emission lines that are used to compute the wavelength solution. In principle, the calibration error in the regions in between ThAr emission lines can be typically of the order of a few hundred metres per second (for example see Agafonova et al. 2011).

All the spectra were corrected for the motion of the observatory around the barycentre of the Sun–Earth system. The velocity component of the observatory’s barycentric motion towards the line of sight to the object was calculated at the exposure mid-point (see Table 1). Conversion of air to vacuum wavelengths was performed using the formula given in Edlén (1966). For the co-addition of the different exposures, we interpolated the individual spectra and their errors to a common wavelength array and then computed the weighted mean using weights estimated from the errors in each pixel. In order to fit the continuum, we considered only specific regions (20–100 Å) around the absorption lines of interest and fitted the points without any absorption with a lower order cubic spline.

Voigt profile fits of the absorptions from different species have been performed using VPFIT, version 9.5. While simultaneously fitting absorption profiles of a system, we assumed that all the singly ionized species (e.g. Fe II, Si II, Zn II, etc.) are kinematically associated with the same gas. We also assumed that the velocity broadening is predominantly turbulent. Therefore, we used the same \( \Delta \) and \( \beta \) parameters for a given component for all the species. The error on the redshift of individual Voigt profile components depends on the statistical error from the fitting procedure and the systematic errors related to the procedure itself and the wavelength calibration. The VPFIT program estimates errors using only the diagonal terms of the covariance matrix. Although the reliability of the errors has been confirmed for unblended components (see King et al. 2009; Carswell et al. 2011), errors from VPFIT are underestimated in the case of blended components. To account for this and other systematic errors discussed above, we perform Voigt profile fits for a given system several times (see Section 2.1.3 for details). Table 2, we summarize the laboratory wavelengths and oscillator strengths of all transitions that are used in this study. In this table, we also give a short name (id) to specific transitions for future reference in the text.

2.1.1 Systematic errors in wavelength calibration

The shortcomings of the ThAr wavelength calibration of quasar spectra taken with VLT/UVES have already been discussed by a number of authors (Chand et al. 2006; Levshakov et al. 2006; Molaro et al. 2008; Thompson et al. 2009; Whitmore, Murphy & Giest 2010; Agafonova et al. 2011). Overall velocity shifts of the order of a few hundred metres per second have been observed between the spectra of the same object calibrated with an iodine cell spectrum or with a ThAr calibration lamp (Whitmore et al. 2010). The latter authors have also shown that intra-order velocity shifts of more than 200 m s\(^{-1}\) are present within a given exposure. Therefore, while we have taken enough care during the data reduction, wavelength uncertainties due to these systematics still remain. We therefore performed several tests to estimate these systematic effects.

2.1.2 Cross-correlation analysis

We cross-correlate individual spectra (in a window comprising of the absorption lines associated with the systems of interest) with the combined spectrum to estimate the velocity offset between them. For this we first rebin each pixel (\( \Delta \delta \approx 2.0 \) km s\(^{-1}\)) to 25 subpixels with a velocity width of \( \approx 80 \) m s\(^{-1}\). This rebinning is done by interpolating the spectrum with a polynomial using Neville’s algorithm (see Fig. 1). For finding the relative shift between the combined spectrum \( I \) and the spectrum \( I_0 \) of the \( i \)th exposure, we proceed as follows: we fix \( I \) and shift \( I_0 \) relative to \( I \) by steps of 0.04 times the original pixel size (i.e. 80 m s\(^{-1}\)). At each step characterized by the shift \( \delta \), a \( \chi^2 \) is calculated from the difference in fluxes between \( I \) and \( I_0 \) and the flux error of \( I \); \( \chi^2(\delta) = \Sigma [I_i - I_{0j}(\delta\lambda)]^2/\sigma_i^2(\delta\lambda) \), where \( I_{0j} \) is the normalized flux of the \( j \)th pixel of the \( i \)th exposure with the error \( \sigma_{ij} \). This \( \chi^2 \) is a function of \( \delta \lambda \) and is minimum
when the two profiles are aligned. We fit the function $\chi^2(\delta\lambda)$ with a parabola, and the value of $\delta\lambda_{\text{min}}$ at which the $\chi^2$ is minimum is taken as the wavelength offset between the two absorption profiles (see Fig. 2). Following the standard statistical procedure, we assign 1σ errors to this $\delta\lambda_{\text{min}}$ by computing the required change in $\delta\lambda$ so that $\Delta\chi^2 = \chi^2 - \chi^2_{\text{min}} = 1$. This procedure is similar to that implemented by Agafonova et al. (2011) to find the shift between their spectra but with the difference that they use the simple sum of the square of the differences in fluxes instead of $\chi^2$. Using $\chi^2$ has the advantage that we can associate an error with the measured shift. For each exposure, we measure the shifts (of all transitions used in our Voigt profile fitting) along with the errors. Having measured a shift and an error for each transition in each exposure, we find their weighted mean and weighted standard deviation as an estimate of the systematic error due to a constant shift in the redshift of the absorbing system. In addition, the correlation analysis not only allows us to identify exposures with abnormally large wavelength shifts but also to identify absorption lines that may be affected by calibration uncertainties in one of the exposures. Results of this exercise for four quasars in our sample are summarized in Tables A1, A2, A3 and A4 of Appendix A. It is clear from these tables that individual exposures have typical (rms) shifts of up to $\sim 350$ m s$^{-1}$.

2.1.3 Repeated Voigt profile fitting analysis

We use simultaneous fitting of several transitions to measure the redshift of a given component and the associated error. To estimate the latter, we perform repeated Voigt profile fitting using several combinations of spectra excluding one exposure at a time. This exercise allows us to understand the influence of individual exposures on our final redshift measurement. Similarly, using the final combined spectra we perform repeated Voigt profile fitting including and excluding different transitions. This will allow us to estimate the redshift uncertainties due to the choice of lines used in the Voigt profile fitting and also the random intra-order shifts.

It is known that the wavelength calibration is most accurate in regions close to the ThAr emission lines that are used to derive the pixel-to-wavelength solution (see Agafonova et al. 2011). Therefore, we performed Voigt profile fitting of those transitions that have at least one ThAr emission line (that was used for wavelength calibration) within $\pm 50$ km s$^{-1}$ from the UV–optical component that coincides with the 21-cm component. We use the results of the above exercises along with the results of the cross-correlation analysis to quantify the final errors in the redshift measurements.

| Source name | Exposure name | Date          | Starting time (UT) | Exposure (s) | Setting | Seeing (arcsec) | Airmass |
|-------------|---------------|---------------|-------------------|-------------|---------|----------------|---------|
|            | EXP1          | 2000-10-21    | 01:15:02          | 3700        | 390+580 | 0.64           | 1.11    |
| J0108−0037 |               |               |                   |             |         |                |         |
| EXP2        | 2000-11-23    | 02:41:45      | 3700              | 390+580     | 0.77    | 1.13           |         |
| EXP3        | 2000-11-25    | 01:52:08      | 3700              | 390+580     | 0.89    | 1.10           |         |
| EXP4        | 2000-12-30    | 01:11:20      | 3690              | 390+580     | 0.71    | 1.10           |         |
| J1623+0718  | EXP1          | 2010-05-08    | 05:48:49          | 3340        | 390+580 | 1.33           | 1.18    |
| EXP2        | 2010-08-07    | 01:08:41      | 3340              | 390+580     | 0.82    | 1.23           |         |
| EXP3        | 2010-08-08    | 00:45:37      | 3340              | 390+580     | 0.86    | 1.20           |         |
| EXP4        | 2010-08-09    | 00:56:50      | 3340              | 390+580     | 0.70    | 1.22           |         |
| J2340−0053  | EXP1          | 2008-10-02    | 02:39:30          | 4500        | 390+580 | 0.88           | 1.13    |
| EXP2        | 2008-10-05    | 02:01:02      | 4500              | 390+580     | 0.82    | 1.17           |         |
| EXP3        | 2008-10-05    | 03:25:10      | 4500              | 390+580     | 0.88    | 1.09           |         |
| EXP4        | 2008-10-06    | 00:28:59      | 4500              | 390+580     | 0.90    | 1.50           |         |
| EXP5        | 2008-10-06    | 01:55:32      | 4500              | 390+580     | 0.79    | 1.18           |         |
| EXP6        | 2008-10-28    | 04:41:03      | 4500              | 390+580     | 0.79    | 1.45           |         |
| J2358−1020  | EXP1          | 2010-08-04    | 06:27:07          | 3340        | 390+580 | 0.75           | 1.10    |
| EXP2        | 2010-08-06    | 04:43:45      | 3340              | 390+580     | 0.69    | 1.40           |         |
| EXP3        | 2010-08-06    | 05:50:01      | 3340              | 390+580     | 0.71    | 1.16           |         |
| EXP4        | 2010-08-06    | 06:55:07      | 3340              | 390+580     | 0.64    | 1.05           |         |
| EXP5        | 2010-08-06    | 08:00:14      | 3340              | 390+580     | 0.65    | 1.04           |         |
| EXP6        | 2010-08-06    | 09:05:21      | 3340              | 390+580     | 0.77    | 1.10           |         |
| EXP7        | 2010-08-07    | 04:53:34      | 3340              | 390+580     | 0.78    | 1.34           |         |
| J0501−0159  | EXP1          | 2000-10-21    | 06:13:17          | 3600        | 437+750 | 0.61           | 1.17    |
| EXP2        | 2000-10-23    | 04:08:46      | 3600              | 436+580     | 0.53    | 1.73           |         |
| EXP3        | 2001-10-16    | 07:20:51      | 5400              | 436+570     | 0.46    | 1.16           |         |
| EXP4        | 2004-10-21    | 04:38:08      | 4500              | 390+564     | 0.63    | 1.25           |         |
| EXP5        | 2004-10-21    | 05:42:38      | 5400              | 390+564     | 0.79    | 1.56           |         |
| EXP6        | 2004-10-21    | 07:05:51      | 3600              | 437+860     | 1.17    | 1.10           |         |
| EXP7        | 2004-10-22    | 04:38:08      | 3600              | 437+860     | 0.84    | 1.29           |         |
| EXP8        | 2004-10-22    | 05:42:42      | 4500              | 390+564     | 0.89    | 1.12           |         |
| EXP9        | 2004-10-22    | 07:05:55      | 4500              | 390+564     | 0.59    | 1.81           |         |
| EXP10       | 2004-10-22    | 08:04:58      | 3360              | 437+860     | 1.00    | 1.09           |         |

Column 1: source name; Column 2: assigned name for the exposure; Column 3: date of observation; Column 4: starting time of exposure; Column 5: exposure time; Column 6: spectrograph settings; Column 7: seeing in arcsec; Column 8: airmass at the beginning of the exposures.
Table 2. Adopted atomic data for different species used in this study.

| Species | id | Wavelength (Å) | Reference | Oscillator strength |
|---------|----|----------------|-----------|--------------------|
| Si ii   | a  | 1808.01288     | 2         | 0.00208            |
| Cr ii   | b1 | 2056.25682     | 2         | 0.1030             |
| Cr ii   | b2 | 2062.23594     | 2         | 0.0759             |
| Cr ii   | b3 | 2066.16391     | 2         | 0.0512             |
| Mn ii   | c1 | 2576.87534     | 2         | 0.361              |
| Mn ii   | c2 | 2594.49669     | 2         | 0.280              |
| Mn ii   | c3 | 2606.45883     | 2         | 0.198              |
| Fe ii   | d1 | 1608.45081     | 3         | 0.0577             |
| Fe ii   | d2 | 1611.2005      | 1         | 0.00138            |
| Fe ii   | d3 | 2249.8768      | 1         | 0.00182            |
| Fe ii   | d4 | 2260.7793      | 2         | 0.00244            |
| Fe ii   | d5 | 2344.2128      | 2         | 0.114              |
| Fe ii   | d6 | 2374.4613      | 2         | 0.0313             |
| Fe ii   | d7 | 2382.7641      | 2         | 0.320              |
| Fe ii   | d8 | 2586.6497      | 2         | 0.0691             |
| Fe ii   | d9 | 2600.17223     | 2         | 0.239              |
| Ni i    | 1  | 1454.841       | 1         | 0.0276             |
| Ni i    | 2  | 1467.259       | 1         | 0.0063             |
| Ni i    | 3  | 1467.756       | 1         | 0.0099             |
| Ni i    | 4  | 1502.148       | 1         | 0.006              |
| Ni i    | 5  | 1703.4111      | 1         | 0.006              |
| Ni i    | 6  | 1708.6041      | 1         | 0.0324             |
| Ni i    | 7  | 1741.5531      | 1         | 0.0427             |
| Ni i    | 8  | 1751.9157      | 1         | 0.0277             |
| Zn ii   | f1 | 2026.13695     | 2         | 0.501              |
| Zn ii   | f2 | 2062.66028     | 2         | 0.246              |
| C i     | g1 | 1560.3092      | 1         | 0.0774             |
| C i     | g2 | 1656.9284      | 1         | 0.149              |
| Mg ii   | h1 | 2026.4758      | 2         | 0.113              |
| Mg ii   | h2 | 2852.9628      | 2         | 1.83               |

References: (1) Morton (2003); (2) Aldenius (2009); (3) Nave & Sansonetti (2011).

2.2 Archival Keck/HIRES spectrum

For two quasars studied here (J2340−0053 and J0501−0159), high-resolution echelle spectra were obtained with Keck/HIRES by Professor Prochaska and collaborators as part of their data base archive for abundance studies in damped Lyman-α absorbers (DLAs; Prochaska et al. 2001, 2007). The wavelength coverage in both cases is less than that of our VLT/UVES spectra. The spectral resolution of the J2340−0053 Keck/HIRES spectrum is roughly the same as our VLT/UVES spectrum (i.e. 6.0 km s$^{-1}$), but its SNR is less than ours. In the case of J0501−0159, the spectral resolution of Keck/HIRES is ~8.0 km s$^{-1}$, and both spectra have comparable SNR. We fit the absorption profiles in the Keck/HIRES in order to compare the results obtained with the two telescopes. This exercise helps us to understand the systematic errors in the wavelength calibration and especially the existence of any global shift between the two spectra.

2.3 GMRT observations and morphology of the background sources

Gupta et al. (2009) used a bandwidth of 1 MHz split into 128 frequency channels in the course of their Giant Metrewave Radio Telescope (GMRT) survey for 21-cm absorption in strong Mg ii absorbers. This yields a velocity resolution of ~4 km s$^{-1}$ channel$^{-1}$. In our new GMRT observations for three sources (J0108−0038, J2340−0053 and J2385−1020), we have used a bandwidth of 0.25 MHz split into 128 channels yielding a channel resolution of ~1 km s$^{-1}$. To increase the spectral SNR, each object was observed for 24–30 h (i.e. in three full synthesis observations). In the case of J1623+0718, a bandwidth of 0.5 MHz was used to adequately cover both the 21-cm components. Spectral resolution in this case is ~2 km s$^{-1}$.

The data were acquired in the two orthogonal polarization channels RR and LL. For the flux density/bandpass calibration of GMRT data, standard flux density calibrators were observed for 10–15 min every two hours. A phase calibrator was also observed for 10 min every 45 min to get reliable phase solutions. The GMRT data were reduced using the National Radio Astronomy Observatory (NRAO) AIPS package following the standard procedures. Special care was taken to exclude the baselines and time stamps affected by the radio frequency interference (RFI). The spectra at the quasar positions were extracted from the RR and LL spectral cubes and compared for consistency. If necessary, a first-order cubic spline was fitted.
to remove the residual continuum. The two polarization channels were then combined to get the Stokes I spectrum which was then shifted to the heliocentric frame. We used the AIPS task CVEL to correct the observed data for the Earth’s motion and rotation. We obtained the mean spectrum weighting the flux by the square of inverse rms in the line-free channels.

2.3.1 Redshift uncertainties

We can use the cross-correlation analysis described in Section 2.1.2 to search for any possible frequency offset between the spectra of the same object obtained at different epochs and through different polarization channels. To avoid the effect of poor SNR, we consider here only J0108−0037. We have useful data obtained during three epochs, and hence six individual spectra to carry out a correlation analysis of individual spectra relative to the final combined one. The results are summarized in Table 3. Here LL, and RR, correspond to the LL and RR polarizations of the i-th observation of this source. The weighted standard deviation of these observed shifts is 122 m s$^{-1}$, and observed values are up to 249 m s$^{-1}$. We will thus consider the systematic error in radio frequency calibration to be 122 m s$^{-1}$ or equivalently $0.4 \times 10^{-6}$ in $\Delta z/x$.

Below, we will give the results of Gaussian fitting of the 21-cm lines using the combined spectrum and spectra obtained through individual polarization channels. The statistical errors in 21-cm redshift determination are found to be much larger than the above-quoted systematic shift.

2.3.2 Milliarcsecond images of the background sources

The five quasars being studied in this work seem to be compact in Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) and GMRT 610-MHz images such that both have 5-arcsec spatial resolution. VLBA L-band 1422-MHz observations of four sources (i.e. excluding J0501−0159) have been obtained as a part of a larger survey of radio sources with DLAs and Mg II absorption systems along their line of sight to understand the relationship between radio structure and the detectability of 21-cm absorption (see Gupta et al. 2012; Srianand et al. 2012). Details of observational setups and data reduction can be found in these papers. The final images of these four sources are shown in Fig. 3.

In Fig. 3, we see that J0108−0037 is clearly resolved into several components at milliarcsecond scales. We note that 73 per cent of the L-band flux density detected in the FIRST image is recovered in our VLBA image with the compact, unresolved component having 53 per cent of the flux density. In the 8-GHz VLBA image, the strong component seen in our L-band VLBA image gets resolved into two distinct components and only one of them may be associated with the optical continuum-emitting region. This makes our task difficult while trying to assign 21-cm absorbers to their UV–optical absorbing counterparts as there is a high probability that additional contribution to the 21-cm absorption may come from gas that is not located along the optical line of sight.

From Fig. 3, we see that the source J1623+0718 is unresolved even at milliarcsecond scales. However, the VLBA observation recovers only 42 per cent of the flux density detected in arcsecond-scale FIRST image. Based on a Gaussian fit to our VLBA image, we derive that the maximum angular extent of the compact component is 4.64 mas. This means that the size of the radio beam at the redshift of the absorber, $z \sim 1.337$, is less than 39 pc. It is likely that this radio source samples the same region of the absorbing gas as the optical source. High-frequency VLBA observations are not available in the literature for this source. In our recent L-band GMRT observations, we find that the flux density of this source at arcsecond scales is similar to what is seen in the FIRST image. This suggests that the $\sim$58 per cent missing flux in our L-band VLBA image may be due to a diffuse, extended radio-emitting component that might have got resolved out at milliarcsecond scale. Therefore, if the absorbing gas is extended beyond 39 pc, then the absorption against this diffuse component may also contribute to our GMRT spectrum. The source J2340−0053 is clearly unresolved in our L-band VLBA image. It is also unresolved in the high-frequency VLBA images taken at 2 and 8 GHz (for example, see Kovalev et al. 2007). The radio flux density shows a peak around 1.4–2.3 MHz with a sharp decrease towards low-frequency end. All this is consistent with the background quasar being a GHz-peaked compact self-absorbed radio source. Using the flux density measurement in the FIRST catalogue, we find that 90 per cent of the L-band flux density in the FIRST image is recovered in the unresolved VLBA component. Gaussian fitting of the L-band VLBA image gives the maximum angular extent of the object to be 1.71 mas. Using the redshift of the 21-cm absorber at $z \sim 1.36$, we estimate the maximum physical size of the quasar radio beam at the position of the absorbing gas to be $\leq 15$ pc. Thus, it is most likely that optical and radio beams sample the same volume of absorbing gas. Therefore, we expect the systematics related to the structure of the background radio source to be minimum in this case.

The source J2358−1020, observed with a resolution of $\sim$20 mas (Fig. 3), is unresolved in our L-band VLBA image. This source remains unresolved even in higher frequency VLBA observations taken at 2 and 8 GHz (Fey & Charlot 2000; Fomalont et al. 2000). Similarly to the case of J2340−0053, this source is a GHz-peaked radio source with a clear turnaround at the low-frequency end. Moreover, in our VLBA observation we recover 74 per cent of the flux detected in FIRST observation. A single Gaussian component fit represents its 1422-MHz VLBA image well. The largest angular size of the source is constrained to be $\leq 3.71$ mas which is equal to $\leq 31$ pc at the redshift of the absorbing system. All this suggests that the optical and radio sight lines probe the same volume of the absorbing gas. Therefore, we expect the systematics related to the radio structure of this background quasar also to be minimum.

The background radio source J0501−0159, also known as PKS 0458−020, exhibits multiple components at arcsecond and milliarcsecond scales. The radio structure of this source is investigated in detail by Briggs et al. (1989) to determine the spatial extent of the $z_{\text{abs}} = 2.04$ absorber 21-cm detected by Wolfe et al. (1985). At 1.6 GHz, the source is resolved into two components that are marginally separated at 1-arcsec resolution (see fig.1 of Briggs et al. 1989). In the 10-mas resolution map at 608 MHz, the frequency that is also close to the redshifted 21-cm frequency of the $z_{\text{abs}} = 1.56$ absorber, the compact ‘core’ at arcsecond scales is further resolved into a jet and a diffuse component (see fig. 2 of Briggs et al. 1989). The radio emission in these different components is strong enough to contribute to the detected 21-cm absorption. Therefore, if the absorbing gas extends over several milliarcseconds, the possibility

| Table 3. Shifts (in units of m s$^{-1}$) between individual 21-cm spectra relative to the combined one for J0108−0037 at the position of 21-cm absorption. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| LL$_{\text{i}}$ | RR$_{\text{i}}$ | LL$_{\text{2}}$ | RR$_{\text{2}}$ | LL$_{\text{3}}$ | RR$_{\text{3}}$ |
| 47 ± 55 | 99 ± 96 | 71 ± 104 | −180 ± 133 | −178 ± 191 | −249 ± 192 |
| Weighted mean | +17 | | | | |
| Weighted standard deviation | 122 | | | | |

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of velocity offsets between radio and optical absorption lines due to the extended radio structure cannot be ruled out in this case.

3 GAUSSIAN FITS TO 21-CM ABSORPTION LINES

3.1 J0108−0037

Gupta et al. (2007) have reported 21-cm absorption from the $z_{\text{abs}} = 1.371$ Mg II system towards J0108−0037. Despite a low rest equivalent width of $\sim 0.3$ Å for the Mg II doublet, other absorption lines of weaker metal transitions are clearly seen even in the Sloan Digital Sky Survey (SDSS) spectrum. Note that $z_{\text{abs}}$ is very close to $z_{\text{em}}$ with an apparent ejection velocity of only $\sim 180$ km s$^{-1}$. The 21-cm absorption is well approximated by a single Gaussian component in the GMRT data with a resolution of 4 km s$^{-1}$ channel$^{-1}$. Subsequently, we observed this system for 25 h spread over three observing runs of similar durations to obtain a spectrum with 1 km s$^{-1}$ channel width. The final 21-cm absorption spectrum is the inverse-variance-weighted mean of these three spectra (see the top panel in Fig. 4). It can be seen from the figure that the absorption profile is smooth and that more than one Gaussian component is required to fit the profile. The smooth broad wing could indicate either a shallow component with a large velocity width or a blend of several weak narrow components as suggested by the fit to metal absorption lines (see Section 4.1). We find that at least three components are needed to obtain a good fit with a reduced $\chi^2$ of 1.1. The result of this fit is overplotted on top of the observed spectrum in Fig. 4. The redshift of the strongest 21-cm component is 1.3709710(11) (see Table 4). The reduced $\chi^2$ is 1.03 for a four-component fit. This suggests that four components are adequate to represent the 21-cm profile. The redshift of the strongest 21-cm component in this case is 1.3709694(53).

3.2 J0501−0159

The sight line towards this quasar is interesting as it covers two 21-cm absorbers at $z = 2.04$ and 1.56 (Wolfe et al. 1985; Kanekar et al. 2009). Kanekar et al. (2010) fitted the 21-cm absorption with a single component at $z_{21} = 1.5605300(25)$ in a spectrum smoothed to a resolution of 1.3 km s$^{-1}$ channel$^{-1}$. Using the pipeline based on the NRAO GBTIDL package, we re-reduced their archived Green Bank Telescope (GBT) data. Details on the GBT data reduction can be found in Srianand et al. (2012). The original data were obtained with two sets of spectral resolutions (i.e. 0.33 and 0.66 km s$^{-1}$ channel$^{-1}$). However, we rebinned the individual spectra to 1.3 km s$^{-1}$ channel$^{-1}$ resolution before combining them. This is done to match the resolution to our GMRT spectra of other.

Figure 3. Contour plots of VLBA images at 1.4 GHz. The restoring beam, shown as the ellipse, and the first contour level (CL) in mJy beam$^{-1}$ are provided at the bottom of each image. The contour levels are plotted as CL × (−1, 1, 2, 4, 8, ...) mJy beam$^{-1}$.
sources. The absorption profile of this 21-cm absorber (shown in the top panel of Fig. 4) shows the existence of two absorbing components. Redshifts obtained from the two-component fit are summarized in Table 4. It can be seen that the spectra obtained in two polarization channels give consistent redshifts for the two components within measurement uncertainties (i.e. 380 and 700 m s$^{-1}$ for the strong and the weak component, respectively).

3.3 J1623+0718

The 21-cm absorption at $z \sim 1.336$ towards J1623+0718 was first reported by Gupta et al. (2009) with two components. Using their spectrum, we measure $z_{21} = 1.3356755(53)$ and $1.3358518(108)$. As the background source and the absorption lines are weak, we re-observed this system for 16.8 h spread over two full synthesis with a channel width of 2 km s$^{-1}$. Unfortunately, the SNR in the final spectrum is not high enough to provide accurate redshift measurements. Therefore, we rebinned our new spectrum to a resolution of 4 km s$^{-1}$ channel$^{-1}$. The redshifts of the two components in the new combined spectrum are $z_{21} = 1.3356782(85)$ and $1.3359118(116)$. While the redshift of the blue component is consistent with the measurement based on the spectrum of Gupta et al. (2009), the redshift of the second component is off by $7.7 \pm 2.0$ km s$^{-1}$ (see Fig. 5). We attribute this to the low optical depth in this component or to the...
The 21-cm absorption along the line of sight towards this quasar was discovered by Gupta et al. (2009). We have acquired additional $3 \times 8$ h of GMRT data at 1 km s$^{-1}$ channel$^{-1}$ resolution. However, these data are found to be unusable due to RFI. So we use here only the GMRT 21-cm absorption spectrum with $\delta v \sim 1$ km s$^{-1}$ channel$^{-1}$, obtained by Gupta et al. (2009) and shown in Fig. 4. The spectrum clearly shows two absorbing components, the bluer being quite strong. The continuous line in Fig 4 shows the double Gaussian fit to the 21-cm absorption profile. The two components are also shown (see also Table 4). The redshifts of the two components are $z = 1.3608595(14)$ and 1.3608874(106). The redshift errors for the Gaussian fits correspond to uncertainties in the velocity scale of 180 and 1350 m s$^{-1}$, respectively. The above redshifts are found to be consistent with those obtained by fitting RR and LL spectra separately (see Table 4).

### 3.4 J2340$-$0053

The 21-cm absorption along the line of sight towards this quasar was first discovered by Gupta et al. (2007). The 21-cm absorption is well approximated by a single Gaussian component at a spectral resolution of 2 km s$^{-1}$ channel$^{-1}$ (Gupta et al. 2009). Two high-resolution spectra of this object with $\delta v \sim 1$ km s$^{-1}$ channel$^{-1}$ were acquired during subsequent observations (2 × 8 h). The shape of the 21-cm absorption feature even at this higher resolution is consistent with a single component (see Fig. 4). This is the simplest profile in our sample. It is best fitted with a single component at $z_{21} = 1.1730206(17)$. The typical error in the redshift measurement is $\sim 230$ m s$^{-1}$. As there are four individual spectra, we also performed a fit using errors that are the rms of the fluxes measured in the different spectra. The fit obtained using these errors gives $z_{21} = 1.1730212(20)$, which is consistent with the above-quoted measurement. In Table 4, we also provide results of independent fits to RR and LL spectra. The $z_{21}$ measurement based on the RR spectrum is higher than the one obtained from the LL spectrum with a relative offset of $1.3 \pm 0.6$ km s$^{-1}$. We find that this is mainly due to presence of low-level RFI affecting the shallow feature. Because of this reason, we do not use this component to constrain $\Delta \nu_{id}$. In order to increase the SNR further, we combined our new spectra with the spectra obtained by Gupta et al. (2009). The Gaussian fit to the combined spectrum is shown in Fig. 4. The fit results are summarized in Table 4. The measured $z_{21} = 1.3356761(51)$ for the main 21-cm component agrees well with the measurements based on spectra obtained in individual polarization channels. The redshift uncertainty in this case corresponds to a velocity of 650 m s$^{-1}$.
to one of the RR spectra being affected by low-level RFI. While this spectrum does not influence the weighted mean I-spectra, the combined RR spectrum is appreciably affected by this. Combining all the spectra but this affected spectrum yields $z_{21} = 1.1730188(25)$ (i.e. with a redshift error corresponding to 344 m s$^{-1}$). This is the $z_{21}$ we use to derive $\Delta x/\Delta x$ for this system.

4 VOIGT PROFILE FITTING OF UV LINES

In this section, we describe the Voigt profile fitting of the UV absorption lines and discuss the individual systems in detail.

4.1 System at $z_{abs} \sim 1.37$ towards J0108$−$0037

J0108$−$0037 is one of the brightest quasars in our sample with an SDSS r-band magnitude of 17.5. The SNR in the continuum close to the absorption lines used for measuring redshifts is usually larger than 30 for this system. The absorption profiles of all singly ionized transitions used in the Voigt profile fits are shown in Fig. 6. Interestingly, many transitions of Ni II are detected in this system. This could allow one to measure $\Delta \alpha/\alpha$ by using only Ni II transitions once accurate values of rest-frame wavelengths, oscillator strengths and sensitivity coefficients are available. Apart from Ni II $\lambda\lambda 1467, 1502, 1703$, other absorption profiles are very strong. Absorption profiles of Fe II $\lambda\lambda 1608, 2344, 2374, 2382, 2586, 2600$ in our final combined UVES spectra are highly saturated and have not been used for redshift measurement. We have fitted this system with two, three, four and five components to find the optimal fit. The reduced $\chi^2$ are, respectively, 1.60, 1.42, 1.28 and 1.23. Increasing the number of components does not lead to any better fit. Therefore, we consider the fit with five components as the best fit for this absorbing system. From our best fit, there are two strong UV absorption components (at $v = 6.4$ and 19.5 km s$^{-1}$ in Fig. 6) with approximately the same column density of metals. This means, unlike in other cases discussed here, a unique identification of the strongest UV component to be associated with the strongest 21-cm component is highly questionable. Even though both 21-cm and UV absorption lines span the same velocity range, there is no one-to-one correspondence between the two. This could mean that the 21-cm optical depth does not scale with the column density of metal lines. To illustrate this, we plot in the bottom-right panel of Fig. 6 a five-component fit of the 21-cm absorption profile. This

![Figure 6](https://example.com/figure6.png)

Figure 6. Voigt profile fits to the absorption profiles of the $z_{abs} \sim 1.37$ system towards J0108$−$0037. The histogram plot in each panel shows the observed absorption profile of a given transition, and the continuous curve is the best Voigt profile fit (or Gaussian fit in the case of 21-cm profiles). The last panel shows the 21-cm absorption profile along with the fitted model and its individual components. The normalized residuals (i.e. ([data]−[model])/[flux error]) for each fit are shown in the top of each panel along with the 1σ horizontal line. The upper vertical tick marks indicate the position of 21-cm absorber components, and the lower vertical tick marks indicate different optical–UV velocity components.
could also mean that an additional contribution to 21-cm absorption comes from gas that is not probed by the optical sight line. As the morphology of the background source is complex, we cannot rule out that the differences in the absorption profiles are due to the fact that the optical and radio sight lines probe different volumes of the absorbing gas. Therefore, because of the degeneracy introduced by this peculiar profile and the complex morphology of the radio emission, we do not use this system for $\Delta\chi^2/s$ measurements.

### 4.2 System at $z \sim 1.33$ towards J1623+0718

J1623+0718 with an SDSS r-band magnitude of $\sim 17.5$ is another bright quasar in our sample. The velocity plots of some of the species detected from the $z_{\text{abs}} \sim 1.33$ system are shown in Fig. 7. The SNR in the continuum close to the absorption profile of Ni II $\lambda 1454$ is $\sim 10$, and it is higher than 30 close to Fe II $\lambda 2586$. The absorption profiles of weak metal transitions like Si II $\lambda 1808$ are spread over 80 km s$^{-1}$. The 21-cm absorption including the broad component is spread over the same velocity range. From visual inspection, it is clear that the strongest metal absorption component coincides well with the main narrow 21-cm component.

The optical absorption profiles suggest the presence of additional weak components in the wings (at $v \sim 53$ and $\sim -20$ km s$^{-1}$). We constrain the component structure in the wings from the strong Fe II lines for which the wings are apparent. The best fitted Voigt profile shown in Fig. 7 has a reduced $\chi^2$ of 1.04. The measured redshift of the strongest metal component in the 21-cm velocity range is $z_{\text{abs}} = 1.3356684(19)$ with the typical redshift error of 240 m s$^{-1}$ (see Table 5).

As can be seen, the main component in the metal absorption is broad and may contain additional hidden narrow components. Therefore, we repeated the fits with additional components injected around the main component. The reduced $\chi^2$ does not change with the addition of these new components. There is however a minor change in the absorption redshifts, albeit with increased errors; for the strongest component we find $z = 1.3356675(47)$ with an error of $\sim 600$ m s$^{-1}$. This is the UV absorption redshift and associated uncertainty we consider for $\Delta\chi^2/s$ measurement.

### 4.3 System at $z_{\text{abs}} \sim 1.36$ towards J2340−0053

In addition to our VLT/UVES spectrum, we have also analysed the Keck/HIRES spectrum of this object. The velocity plot of different ions detected in this system is shown in Figs 8 and 9. The SNR in the UVES continuum is $\sim 40$ close to Ni II $\lambda 1709$ and can be larger than 60 close to Mn II absorptions. The absorption lines of singly

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Figure 7. Same as Fig. 6 for the $z_{\text{abs}} \sim 1.33$ Mg II system towards J1623+0718.

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Table 5. Results of repeated Voigt profile fitting analysis.

| Quasar     | $z_{UV}$ | $\delta v$ (km s$^{-1}$) | $\delta v_a$ (km s$^{-1}$) | id  | $\delta v_a$ (km s$^{-1}$) | id  | $\delta v_a$ (km s$^{-1}$) | id  | $\delta v_a$ (km s$^{-1}$) | id  | $\delta v_a$ (km s$^{-1}$) | id  |
|------------|----------|---------------------------|-----------------------------|-----|-----------------------------|-----|-----------------------------|-----|-----------------------------|-----|-----------------------------|-----|
| J1623+0718 | 1.335    | $-0.02 \pm 0.23$          |                             | d2  | $+0.34 \pm 0.31$           | d5  | $+0.36 \pm 0.26$           | d2  | $-0.23 \pm 0.22$           |     |                             |     |
| J2340−0053 | 1.360    | $+0.26 \pm 0.18$          |                             | d2  | $-0.22 \pm 0.19$           | d8  | $-0.48 \pm 0.33$           | c7  | $+0.09 \pm 0.46$           | d2  | $-0.07 \pm 0.15$           |     |
| J2358−1020 | 1.173    | $+0.26 \pm 0.47$          |                             | f1  | $-0.01 \pm 0.37$           | d9  | $-0.54 \pm 0.44$           |     |                             | d5  | $-0.02 \pm 0.23$           |     |
| J0501−0159 | 1.560    | $+0.35 \pm 0.27$          |                             | b2  | $+0.26 \pm 0.30$           | d9  | $+0.15 \pm 0.67$           | b3  | $-0.52 \pm 3.23$           |     | $+0.07 \pm 0.17$           |     |

Column 1: source name; Column 2: the absorption redshifts and associated error (in brackets) measured using our VLT/UVES spectrum; Column 3: error in the redshift measurement given in Column 2 in km s$^{-1}$; Column 4: measured velocity offset when excluding weak transitions (as defined in Table 2) listed in Column 5; Column 6: measured velocity offset when a saturated line (with ids given in Column 7) is included in the fit; Column 8: velocity offset measured after excluding the absorption lines (whose ids are given in Column 9) far away from the ThAr lamp lines used for wavelength calibration; Column 10: measured velocity offset for the redshift measured using the Keck/HIRES spectrum. Column 11: mean and standard deviation of measured redshifts after removing one exposure from combined spectra (see Fig. 12).

$^a$ All the velocities and associated errors are calculated with respect to the main redshift given in the second column.

![Figure 8](https://academic.oup.com/mnras/article-abstract/425/1/556/1001508)

Figure 8. Same as Fig. 6 for the $z_{abs} \sim 1.36$ Mg II absorber towards J2340−0053 and for the VLT/UVES. In the bottom-right corner panel, we zoom over 40 km s$^{-1}$ to show the 21-cm absorber with the two components fit overplotted.

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ionized species are spread over $\sim 150$ km s$^{-1}$. Unlike in the case of J1623+0718 and J0108–0037, the 21-cm absorption is very much narrower than the UV absorption lines. However, as pointed out by Gupta et al. (2009), the metal component associated with the 21-cm component is well detached. In particular, the component is well defined by the Si ii $\lambda$1808 and Zn ii lines. Note that we have not fitted the absorption profile of Si ii for $v < -55$ km s$^{-1}$ as this region is contaminated by absorption from another intervening system. The fit has a reduced $\chi^2$ of 1.3. The overall profile is fitted with 14 Voigt profile components, and the absorption coinciding with the 21-cm absorption requires two narrow components.

The redshifts of the two UV–optical components in our UVES spectrum that are closer to 21-cm absorption are $1.360\ 8565(16)$ and $1.360\ 8781(19)$. The former happens to be the stronger absorption component to be associated with the stronger 21-cm absorption component. The redshift errors due to Voigt profile fitting correspond to 200 and 240 m s$^{-1}$ for these components. The redshifts measured from the HIRES spectrum, $1.360\ 8572(36)$ and $1.360\ 8759(40)$, are consistent with those derived from the UVES spectrum. The fitting errors in the redshifts for the HIRES data are 457 and 508 m s$^{-1}$, respectively.

### 4.4 System at $z_{\text{abs}} \sim 1.17$ towards J2358–1020

J2358–1020 with an $r$-band SDSS magnitude of 18.7 is one of the faintest quasars in our sample. The SNR in the UVES spectrum is at best $\lesssim 25$. As can be seen in Fig. 10, the absorption profiles are spanning more than 150 km s$^{-1}$. Absorption profiles of Cr ii $\lambda\lambda\ 2056, 2062, 2066$, Mn ii $\lambda\lambda\ 2594, 2606$ are not used in the fit as they are weak or located in regions of poor SNR. As there are weak components at $v \sim -140$ and 15 km s$^{-1}$, we included two core-saturated profiles, Fe ii $\lambda\lambda\ 2344$ and 2586, to be able to fit the overall profile. Similar to the case of J2340–0053, the metal component coinciding with the 21-cm absorption seems to be well detached from other components and is well fitted with a single Voigt profile component. This is apparent for Si ii $\lambda$1808, Zn ii $\lambda$2026.
and $\text{Mn II} \lambda 2576$. The overall fit has 11 Voigt profile components with a reduced $\chi^2$ of 1.2.

The redshift of the stronger absorption component that we associate with the 21-cm absorption is $1.1730227(29)$. The redshift error from line fitting is $\sim 400$ m s$^{-1}$.

4.5 System at $z_{\text{abs}} \sim 1.56$ towards J0501−0159

J0501−0159 is a faint quasar with an $r$-band magnitude of 19.33. Similar to the case of J2340−0053, we have spectra obtained with VLT/UVES as well as Keck/HIRES. Fig. 11 presents the velocity plot of different absorption profiles detected in this system. The top and bottom panels show the VLT/UVES and Keck/HIRES spectra, respectively, along with their best-fitting profiles. Although the final combined UVES/VLT spectrum is made up of 10 exposures each of more than 3300 s of exposure time, the typical SNR is only $\lesssim 20$. Apart from those $\text{Fe II}$ lines that are shown in Fig. 11, other $\text{Fe II}$ lines are highly saturated or have poor SNR. Associated $\text{Ni II}$ absorption lines are very weak and are not used for the Voigt profile fitting. Some of them are located in the Lyman $\alpha$ forest, others are either contaminated or have poor SNR and therefore have not been included in the fit. Our best fit is shown in Fig. 11 and has a reduced $\chi^2$ of 1.0.

It can be seen in Fig. 11 that the strongest 21-cm component coincides with the strongest metal component seen in the absorption profiles of undepleted species like $\text{Zn II}$ and $\text{Si II}$. The redshifts of the UV–optical component in UVES and HIRES data are, respectively, 1.5605354(43) and 1.5605398(276) with errors of 503 and 3234 m s$^{-1}$. The two measurements agree within 1.0$\sigma$.

5 CONSTRUING $\Delta x/x$

In this section, we present $\Delta x/x$ measurements for individual systems and discuss the associated errors in detail. We measure $\Delta x/x$ using

$$\Delta x = \frac{z_{\text{UV}} - z_{21}}{1 + z_{21}}; \quad (1)$$

where $z_{\text{UV}}$ is the redshift of the UV–optical component as given in Column 2 of Table 5 and $z_{21}$ is the redshift of the 21-cm component as given in Column 3 of Table 4. Usually the metal absorption has a larger velocity spread compared to that of the 21-cm absorption. So to associate the UV–optical absorption (i.e. $z_{\text{UV}}$) with the 21-cm component, we use the stronger absorption component in the velocity range of the 21-cm absorption. In all cases discussed here, the UV–optical absorption clump associated with the 21-cm absorption is easily identifiable. The statistical error due to the fits, $\sigma(\Delta x/x)$, is calculated as

$$\sigma(\Delta x/x) = \sqrt{\frac{1}{1 + z_{21}} \left( \left( \frac{1 + z_{\text{UV}}}{1 + z_{21}} \right)^2 \times \sigma_{z_{21}}^2 + \sigma_{z_{\text{UV}}}^2 \right)}, \quad (2)$$

where $\sigma_{z_{\text{UV}}}$ and $\sigma_{z_{21}}$ are the errors on $z_{\text{UV}}$ and $z_{21}$, respectively. In the case of $\sigma_{z_{21}}$, we consider the contributions of statistical (Table 4) and systematic uncertainties (Table 3), the latter being smaller ($\lesssim 122$ m s$^{-1}$) than the former ($\gtrsim 300$ m s$^{-1}$). To estimate the systematic errors in the optical redshifts, we carry out a number of tests whose results are summarized in Table 5 and also in the tables of Appendix A (see Section 2.1 for more detail). In Columns 4, 6 and 8 of Table 5, we give velocity offsets measured with respect to $z_{\text{abs}}$ given in Column 2 using repeated Voigt profile fitting after, respectively, excluding weak lines, including saturated lines and excluding the absorption lines with no ThAr line within 50 km s$^{-1}$ of that optical component assigned to the 21-cm component. The references to the corresponding lines are given in the preceding column. The results of these tests are sensitive to the intra-order wavelength calibration errors. To be on the conservative side, we consider the maximum

\[\Delta x = \frac{z_{\text{UV}} - z_{21}}{1 + z_{21}}; \quad (1)\]

\[\sigma(\Delta x/x) = \sqrt{\frac{1}{1 + z_{21}} \left( \left( \frac{1 + z_{\text{UV}}}{1 + z_{21}} \right)^2 \times \sigma_{z_{21}}^2 + \sigma_{z_{\text{UV}}}^2 \right)}, \quad (2)\]
Figure 11. Same as Fig. 6 for the $\zabs \sim 1.56\ Mg\ II$ absorber towards J0501−0159 from the VLT/UVES spectrum (top) and HIRES/Keck spectrum (bottom).

The error found here as a measure of the systematic error introduced from intra-order shifts ($\sigma_e$).

In Column 11 of Table 5, we give the mean velocity offset found by repeated Voigt profile fitting of lines after excluding one of the exposures (see also Fig. 12). Tables in Appendix A also summarize the results of cross-correlation analysis between the individual exposures and the combined spectra. The results of the last two exercises (exposure removal and cross-correlation) are sensitive to
these errors are converted from velocity shifts to $\Delta x/\alpha$. In Column 7 of Table 6, we present the total systematic error, $\sigma_{\text{sys}}$, which is calculated from the quadratic sum of $\sigma_{e}$, $\sigma_{c}$ and 122 m s$^{-1}$ we found from 21-cm analysis.

6 RESULTS AND CONCLUSIONS

In Table 6, we summarize the $\Delta x/\alpha$ measurements in individual systems. We recollect that the values are obtained under the assumption that the strongest UV and 21-cm absorption are produced by the same gas. The final errors in $\Delta x/\alpha$ for our VLT/UVES measurements given in Column 8 are the quadratic sum of the statistical and systematic errors. We find the simple mean of $\Delta x/\alpha$ regardless of the associated errors in individual measurements to be $(0.0 \pm 1.5) \times 10^{-6}$ with an rms of $3.0 \times 10^{-6}$ around the mean. A constant $\Delta x/\alpha$ of $0.0 \times 10^{-6}$ has a reduced $\chi^2$ of 1.0 for our four UVES measurements that show that the estimated errors in $\Delta x/\alpha$ are not underestimated. If we apply the standard procedure of weighting the data points by their inverse square errors (given in Column 8 of Table 6), we get $-(0.1 \pm 1.3) \times 10^{-6}$.

Our VLBA images suggest that two of the quasars in the sample (i.e. J1623+0718 and J0501−0159) may have resolved structures at milliarcsecond scale containing more than 50 per cent of the flux. This may imply that if the absorbing gas is extended, then some additional 21-cm absorption can originate from the gas that is not probed by the optical sight lines. However, in the remaining two quasars this is not the case as most of the flux is recovered in the unresolved VLBA component. If we only use these two cases, we derive $\Delta x/\alpha = +(0.2 \pm 1.6) \times 10^{-6}$. This is very much consistent with what we find using all the four systems. Therefore, the analysis presented here does not find any statistically significant variation in $x$ and this null result may not be related to systematics due to radio structure.

There are two quasars for which we have spectra from both VLT and Keck. As can be seen from Table 6, in both cases the VLT and Keck measurements are consistent with each other with Keck measurements having larger statistical uncertainties. The mean $\Delta x/\alpha$ from VLT/UVES data of $(0.0 \pm 1.5) \times 10^{-6}$ is consistent with $\Delta x/\alpha = +(1.8 \pm 2.8) \times 10^{-6}$ from Keck/HIRES data, where we could not include the systematic error. This is also the case for the weighted means.

In Fig. 13, we compare our $\Delta x/\alpha$ results with other $\Delta x/\alpha$ measurements from the literature. The filled circles are our measurements.

The final errors in $\Delta x/\alpha$ from Keck/HIRES data, where we apply the standard procedure of weighting the data points by their inverse square errors (given in Column 8 of Table 6), we get $-(0.1 \pm 1.3) \times 10^{-6}$.

| Quasar | $z_{\text{abs}}$ | $\Delta x/\alpha$ | $\sigma_{\text{stat}}$ | $\sigma_{e}$ | $\sigma_{c}$ | $\sigma_{\text{sys}}$ | $\sigma_{\text{tot}}$ | $\Delta a/\alpha$ | $\Theta$ | $\Delta a/\alpha$ |
|--------|----------------|------------------|------------------|--------|--------|--------|-------|----------------|--------|----------------|
| J1623+0718 | 1.3356 | $-3.7$ | 3.0 | 1.0 | 1.2 | 1.6 | 3.4 | $-1.8 \pm 1.7$ | $\pm 6.0$ | $+3.9 \pm 1.6$ | $+5.7 \pm 2.3$ |
| J2340−0053 | 1.3608 | $-1.3$ | 0.9 | 0.7 | 1.6 | 1.7 | 2.0 | $-0.6 \pm 1.0$ | $\pm 1.0 \pm 1.6$ | $0.9 \pm 1.1$ | $+0.5 \pm 1.6$ |
| J2358−1020 | 1.1730 | $+1.8$ | 1.8 | 0.8 | 1.8 | 2.0 | 2.7 | $+0.9 \pm 1.4$ | $\pm 84.9$ | $+0.8 \pm 1.1$ | $-0.1 \pm 1.8$ |
| J0501−0159 | 1.5605 | $+3.0$ | 2.1 | 0.6 | 2.2 | 2.3 | 3.1 | $+1.5 \pm 1.6$ | $\pm 119.0$ | $-5.2 \pm 1.8$ | $-6.7 \pm 2.4$ |

Table 6. $\Delta x/\alpha$ measured (in units of $10^{-6}$) from different absorption systems.

- Column 1: object name; Column 2: absorption redshift; Columns 3–8: $\Delta x/\alpha$ measurement, associated statistical and systematic errors (as discussed in Section 5), respectively; Column 9: $\Delta a/\alpha$ calculated based on the final values for $\Delta x/\alpha$ assuming constancy of other constants; Column 10: $\Delta x/\alpha$ measurements based on Keck/HIRES data; Columns 11 and 12: angular distance in degrees between the quasar sight line and the best fitted dipole position from Webb et al. (2011) and the predicted value for $\Delta a/\alpha$ based on dipole; Column 13: difference between our measurement and the prediction from dipole and its associated error.

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The dash–dotted rectangular box indicates the mean and standard deviation of our measurements. The solid rectangular box gives the mean and final error on it when combining the four measurements. The green box with the dashed line gives the weighted mean and 1σ found by Tzanavaris et al. (2007). The two filled stars are from Kanekar et al. (2010), and the empty star is from Kanekar et al. (2006, 2010).

The better accuracy reached in our study is mainly due to the following reasons: (1) systems are chosen to have narrow 21-cm absorption components. (2) Three of the quasars have high-resolution (R ~ 45000) and high-SNR UV–optical spectra obtained specifically for constraining \( \Delta \lambda / \Delta z \) with attached ThAr calibration lamps for each spectrum. This minimizes the systematic error of wavelength calibration. (3) Very high (~1 km s\(^{-1}\) channel\(^{-1}\)) or high (2–4 km s\(^{-1}\) channel\(^{-1}\)) resolution 21-cm spectra are used. (4) As we could get repeated observations for 21-cm absorptions, we are able to identify the RFI-related problems in the absorption profiles. (5) We also estimate \( \Delta \lambda / \Delta z \) by using only absorbers for which the background sources are unresolved even at milliarcsecond scale in VLBA images.

Although tight constraints on the variation of fundamental constants are obtained by comparing 21-cm and UV–optical redshifts, the method is not exempt of systematics like all other methods in this field. As has already been discussed, the main source of uncertainty on \( \Delta \lambda / \Delta z \) is related to the assumption used to associate one of the several UV–optical components with the 21-cm absorption. By choosing absorbers with compact background radio sources at mas scale, one can minimize the uncertainties related to the possibility that optical and radio sight lines are different. Different methods have been implemented to associate the UV–optical component with the 21-cm one. Tzanavaris et al. (2007) associated the pixel with strongest UV–optical optical depth with the pixel with strongest 21-cm optical depth. In this work, we follow the same idea but using components of simultaneous Voigt profile fitting models.

Using the same method as Tzanavaris et al. (2007), we find \( \Delta \lambda / \Delta z = (3.6 \pm 3.1) \times 10^{-6} \). Keeping this in mind, we will now discuss the implication of our constraint on \( \Delta \lambda / \Delta z \) on the variation of individual constants that constitute \( x \).

As \( x = g_\alpha \tau^2 / \mu \), its variation can be related to the variation of \( g_\alpha \), \( \alpha \) and/or \( \mu \) via \( \Delta \lambda / \Delta z = \Delta g_\alpha / g_\alpha + 2 \times \Delta \alpha / \mu - \Delta \mu / \mu \). Therefore, the constancy of \( x \) can be related either to the constancy of all the three constants, \( g_\alpha \), \( \alpha \), and \( \mu \), or to some complicated combination of variations of these constants with an overall null effect on \( x \).

Assuming \( \mu \) and \( g_\alpha \) are constants, then our measured \( \Delta \lambda / \Delta z \) translates to \( \Delta \alpha / \alpha = (0.0 \pm 0.8) \times 10^{-6} \) which is one of the most stringent constraints on the variation of \( \alpha \). In Fig 14, we summarize the available constraints on \( \Delta \alpha / \alpha \) from the literature. It is clear that our measurements are consistent with \( \Delta \alpha / \alpha = (0.1 \pm 1.5) \times 10^{-6} \) (and a factor of 2 better than that) found by Srianand et al. (2007) and with the results of Webb et al. (2011) for \( z \leq 1.8 \) UVES data. Even if we use the conservative approach of Tzanavaris et al. (2007), we get \( \Delta \alpha / \alpha = (1.8 \pm 1.5) \times 10^{-6} \) which is as good as the results from the MM method.

Webb et al. (2011) used a combined set of absorbers observed with VLT/UVES and Keck/HIRES to conjecture about the possible presence of a spatial dipole pattern in the variation of \( \alpha \). Their best fitted model indicates a spatial dipole in the direction with right ascension \( 17.5 \pm 0.9 \) h and declination \( -58 \pm 9 \) °, significant at the 4.2\( \sigma \) level with \( \Delta \alpha / \alpha = \cos(\Theta)(\sin^2(\Theta))^{-1/2} \times 10^{-6} \). In Fig 14, we summarize the available constraints on \( \Delta \alpha / \alpha \) from the literature. It is clear that our measurements are consistent with \( \Delta \alpha / \alpha = (0.1 \pm 1.5) \times 10^{-6} \) (and a factor of 2 better than that) found by Srianand et al. (2007) and with the results of Webb et al. (2011) for \( z \leq 1.8 \) UVES data. Even if we use the conservative approach of Tzanavaris et al. (2007), we get \( \Delta \alpha / \alpha = (1.8 \pm 1.5) \times 10^{-6} \) which is as good as the results from the MM method.

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Constraining fundamental constants at z \sim 1.3

Figure 15. Comparison of $\Delta\mu/\mu$ estimated in this work with other measurements in the literature. The dash-dotted line and the surrounded solid box show our measured $\Delta\mu/\mu$ and its error based on our $\Delta\alpha/\alpha$ measurements and assuming that $\alpha$ and $g_\alpha$ do not vary. Apart from the filled square at $z \sim 3.2$ which is calculated from $\Delta\alpha/\alpha$ of Srianand et al. (2010) with the assumption of non-variation of other constants, the rest of the measurements for $z > 2$ are based on the analysis of H$_2$ electronic transitions. The empty triangle towards up is from Thompson et al. (2009) and filled triangles towards down from Thompson et al. (2009) and filled triangles towards up from Reinhold et al. (2006). The two measurements at $z \leq 1$ are based on the molecular inversion and rotational transitions. The filled and empty squares are from Henkel et al. (2008) and Murphy et al. (2008), respectively.

with null variation as also predicted by the dipole. In the case of J1337+3152, Srianand et al. (2010) measured $\Delta\alpha/\alpha = -(1.7 \pm 1.7) \times 10^{-6}$ for the absorber at $z_{ah} = 3.174$ which translates to $\Delta\alpha/\alpha = -(0.9 \pm 0.9) \times 10^{-6}$. The dipole prediction in this case is $\Delta\alpha/\alpha = -(2.70 \pm 1.9) \times 10^{-6}$ with a difference of $-(1.80 \pm 2.1) \times 10^{-6}$ with the measurement. The difference between these five measurements and the dipole predictions results in a $\chi^2$ of $14.5$. The probability of $\chi^2 > 14.5$ is $\sim 1$ per cent, which implies that the existence of a dipole is not favoured by our measurements. More independent measurements especially towards systems where the dipole predicts large variations will be useful to confirm/refute the existence of the $\alpha$ dipole at higher significant level.

Assuming that $\alpha$ and $g_\alpha$ have been constant, we derive $\Delta\mu/\mu = (0.0 \pm 1.5) \times 10^{-6}$. Fig. 15 compares our results with other direct measurements of $\Delta\mu/\mu$ obtained either using rotational transitions of H$_2$ and HD molecules (for $z > 2.0$) or based on the comparison of NH$_3$ inversion transitions with some rotational transition lines (e.g. CO, CS, HCN; for $z \leq 1.0$). While the constraints we get are not as good as the one obtained using NH$_3$, they are very stringent compared to those based on H$_2$ at $z \geq 2$. What is more interesting is that our measurements fill the redshift gap between NH$_3$- and H$_2$-based measurements (see Fig. 15).

If we use the 1σ constraints on $\Delta\alpha/\alpha$ found for $z \leq 1.8$ absorbers (from Srianand et al. 2007; Webb et al. 2011) and $\Delta\mu/\mu$ estimated at $z \sim 0.7$ using NH$_3$ (Kanekar 2011), considering they are valid at $z \sim 1.3$, we get $\Delta\mu/\mu > 3.5 \times 10^{-6}(1\sigma)$ from our $\Delta\alpha/\alpha$ measurements.

In summary, using 21-cm and metal UV absorption lines we are able to derive stringent constraints on the variation of $\alpha$, $\mu$ and $g_\alpha$. As discussed before, the best estimate on $\Delta\mu/\mu$ at $z \leq 1$ is obtained by comparing the frequencies of NH$_3$ inversion transitions with rotational transitions of other molecules. The existing two measurements are towards the line of sight of two well-known gravitationally lensed BL Lacs (B0218+357 and PKS 1830–211) that show complex radio morphologies. As different transitions occur at different frequencies, the dependence of the background radio structure on frequency is an important source of systematic error (see Murphy et al. 2008; Kanekar 2011). Therefore detecting NH$_3$ and other molecules towards unlensed compact radio sources is important to constrain $\Delta\mu/\mu$. Unlike NH$_3$ and other complex heavy molecules, the 21-cm absorption is more frequently detected towards normal radio sources covering a wide redshift range. The main source of systematics in this method is related to how accurately the 21-cm absorption component is associated with the corresponding metal line component. More measurements towards compact radio sources are needed to address this issue adequately. Future blind searches for the 21-cm absorption using the upcoming Square Kilometre Array path finders hopefully will provide a large number of suitable targets to perform such measurements.

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APPENDIX A: RESULTS OF CORRELATION ANALYSIS
Table A1. Shifts of individual spectra relative to the combined one in J0108−0037 at the position of different absorption profiles.

| Species | EXP1 (m s\(^{-1}\)) | EXP2 (m s\(^{-1}\)) | EXP3 (m s\(^{-1}\)) | EXP4 (m s\(^{-1}\)) |
|---------|----------------------|----------------------|----------------------|----------------------|
| Ni \(\lambda\)1454 | 656 ± 505 | −826 ± 681 | 531 ± 458 | −536 ± 463 |
| Ni \(\lambda\)1467 | −131 ± 595 | −1081 ± 835 | −973 ± 764 | 484 ± 534 |
| Ni \(\lambda\)1502 | −1094 ± 556 | 925 ± 887 | 62 ± 816 | 65 ± 941 |
| Ni \(\lambda\)1703 | −391 ± 359 | 169 ± 473 | 1306 ± 778 | 161 ± 618 |
| Ni \(\lambda\)1709 | −11 ± 184 | 230 ± 211 | −408 ± 227 | 43 ± 195 |
| Ni \(\lambda\)1741 | −145 ± 142 | 275 ± 164 | −160 ± 171 | −98 ± 162 |
| Ni \(\lambda\)1751 | −496 ± 204 | 240 ± 221 | 165 ± 223 | −152 ± 211 |
| Cr \(\lambda\)2056 | −149 ± 109 | 109 ± 121 | 133 ± 135 | −80 ± 121 |
| Cr \(\lambda\)2062 | −83 ± 117 | −168 ± 130 | 99 ± 139 | 151 ± 132 |
| Cr \(\lambda\)2066 | −66 ± 162 | 15 ± 176 | −267 ± 202 | 220 ± 179 |
| Mn \(\lambda\)22576 | 32 ± 102 | 115 ± 111 | −44 ± 110 | −123 ± 105 |
| Mn \(\lambda\)22594 | −176 ± 133 | −220 ± 151 | 181 ± 150 | 156 ± 142 |
| Mn \(\lambda\)22606 | −187 ± 149 | 607 ± 173 | −181 ± 168 | −140 ± 165 |
| Zn \(\lambda\)2026 | −207 ± 166 | 234 ± 188 | −209 ± 194 | 170 ± 184 |
| Zn \(\lambda\)2062 | −108 ± 166 | 79 ± 175 | −267 ± 198 | 218 ± 182 |
| Fe \(\lambda\)1611 | −282 ± 228 | 74 ± 290 | 752 ± 305 | −373 ± 267 |
| Fe \(\lambda\)2249 | −145 ± 103 | 80 ± 110 | −118 ± 116 | 182 ± 118 |
| Fe \(\lambda\)2260 | −358 ± 90 | 300 ± 100 | −56 ± 105 | 183 ± 106 |
| Si \(\lambda\)1808 | −237 ± 108 | 132 ± 127 | 239 ± 138 | −50 ± 124 |
| Weighted mean | −171 | +127 | −14 | +38 |
| Weighted standard deviation | 152 | 207 | 223 | 166 |
| Weighted standard deviation of all exposures | 134 | | | |

Table A2. Shifts of individual spectra relative to the combined one in J1623+0718 at the position of different absorption profiles.

| Species | EXP1 (m s\(^{-1}\)) | EXP2 (m s\(^{-1}\)) | EXP3 (m s\(^{-1}\)) | EXP4 (m s\(^{-1}\)) |
|---------|----------------------|----------------------|----------------------|----------------------|
| Ni \(\lambda\)1454 | 2075 ± 573 | −414 ± 582 | 94 ± 393 | −840 ± 364 |
| Ni \(\lambda\)1703 | 2230 ± 1013 | −531 ± 682 | 378 ± 446 | −414 ± 419 |
| Ni \(\lambda\)1709 | −161 ± 465 | 520 ± 414 | 485 ± 499 | −1040 ± 414 |
| Cr \(\lambda\)2062 | 177 ± 564 | −180 ± 341 | −191 ± 530 | 242 ± 274 |
| Cr \(\lambda\)2066 | −434 ± 687 | 461 ± 633 | 335 ± 745 | −684 ± 602 |
| Zn \(\lambda\)2062 | −1434 ± 643 | 461 ± 633 | 72 ± 615 | 460 ± 408 |
| Mn \(\lambda\)2576 | 498 ± 426 | 0 ± 346 | 235 ± 420 | −217 ± 224 |
| Mn \(\lambda\)2594 | −46 ± 458 | 80 ± 303 | 572 ± 386 | −185 ± 213 |
| Mn \(\lambda\)2606 | 475 ± 481 | −1068 ± 735 | −1073 ± 574 | 194 ± 283 |
| Fe \(\lambda\)1611 | 2002 ± 612 | 1394 ± 770 | 766 ± 1559 | −432 ± 335 |
| Fe \(\lambda\)2249 | −555 ± 389 | 500 ± 273 | −415 ± 424 | −70 ± 305 |
| Fe \(\lambda\)2260 | 342 ± 320 | 635 ± 322 | −632 ± 366 | −164 ± 194 |
| Fe \(\lambda\)2374 | −55 ± 184 | 678 ± 161 | −913 ± 193 | 8 ± 110 |
| Fe \(\lambda\)2382 | −275 ± 142 | 460 ± 139 | −329 ± 160 | 25 ± 89 |
| Fe \(\lambda\)2586 | 196 ± 160 | 451 ± 139 | −237 ± 158 | −307 ± 87 |
| Si \(\lambda\)1808 | 142 ± 261 | 224 ± 220 | 414 ± 253 | −381 ± 180 |
| Weighted mean | +44 | +401 | −233 | −145 |
| Weighted standard deviation | 543 | 314 | 480 | 251 |
| Weighted standard deviation of all exposures | 313 | | | |
Table A3. Shifts of individual spectra relative to the combined one in J2340–0053 at the position of different absorption profiles.

| Species               | EXP1     | EXP2     | EXP3     | EXP4     | EXP5     | EXP6     | HIRES     |
|-----------------------|----------|----------|----------|----------|----------|----------|-----------|
|                       | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) |
| Mn II λ1709           | –645 ± 358 | 212 ± 428 | 144 ± 336 | 759 ± 455 | 380 ± 412 | 74 ± 345 | 2530 ± 296 |
| Mn II λ1741           | –81 ± 380  | 5 ± 361   | 447 ± 296 | 668 ± 321 | 97 ± 282  | –958 ± 317 | 626 ± 232  |
| Ni II λ1751           | –409 ± 513 | –122 ± 392| 588 ± 297 | –180 ± 373| –406 ± 354| 142 ± 332 | 65 ± 521   |
| Cr II λ2056           | –169 ± 759 | 303 ± 868 | 139 ± 761 | –307 ± 922| 263 ± 811 | –41 ± 555 | –43 ± 196  |
| Cr II λ2062           | –206 ± 749 | 184 ± 747 | 217 ± 574 | 49 ± 927  | –213 ± 574| –467 ± 604| 244 ± 268  |
| Mn II λ2066           | 728 ± 1026| –646 ± 1201| 233 ± 988 | –561 ± 1246| 74 ± 1179 | –464 ± 1042| –         |
| Zn II λ2026           | 155 ± 425  | 130 ± 486 | –88 ± 377 | –692 ± 389| 205 ± 290 | 194 ± 325 | –         |
| Mn II λ2576           | –197 ± 351 | 219 ± 407 | 487 ± 400 | –10 ± 384 | –13 ± 368 | –209 ± 290 | –         |
| Mn II λ2594           | –621 ± 375 | 129 ± 370 | 122 ± 384 | –41 ± 363 | 476 ± 361 | –110 ± 274 | –         |
| Mn II λ2606           | –143 ± 317 | –439 ± 405| 885 ± 310 | –139 ± 361| 436 ± 298 | –1199 ± 284| –         |
| Fe II λ1608           | –309 ± 66  | 117 ± 72  | 275 ± 62  | –48 ± 81  | 113 ± 68  | –205 ± 65 | 47 ± 48    |
| Fe II λ1611           | –15 ± 408  | 128 ± 385 | 66 ± 287  | 281 ± 493 | –325 ± 532| –764 ± 456| 2271 ± 539|
| Fe II λ2249           | –103 ± 184 | –104 ± 260| –221 ± 198| –307 ± 195| 171 ± 183 | 138 ± 149 | –433 ± 193|
| Fe II λ2260           | –1272 ± 138| 208 ± 133 | 110 ± 117 | 43 ± 136  | 594 ± 109 | 132 ± 101 | –27 ± 21   |
| Fe II λ2374           | –308 ± 41  | 185 ± 41  | 230 ± 37  | 35 ± 40   | 315 ± 35  | –294 ± 32 | 148 ± 57   |
| Si II λ1808           | –380 ± 139 | –137 ± 160| 357 ± 144 | 122 ± 154 | 249 ± 157 | –165 ± 134| –229 ± 92  |
| Weighted mean         | –352      | 146       | 236       | 18        | 283       | –238       | 110        |
| Weighted standard deviation | 296     | 127       | 148       | 173       | 184       | 238       | 438        |
| Weighted standard deviation of all exposures | 204$^a$ |

$^a$Standard deviation in the HIRES column is not included in the averaged standard deviation.

Table A4. Shifts of individual spectra relative to the combined one in J2358–1020 at the position of different absorption profiles.

| Species               | EXP1     | EXP2     | EXP3     | EXP4     | EXP5     | EXP6     | EXP7     |
|-----------------------|----------|----------|----------|----------|----------|----------|----------|
|                       | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) |
| Zn II λ2026           | –509 ± 549 | –477 ± 376 | –744 ± 629 | 1083 ± 395 | 173 ± 266 | 165 ± 326 | –511 ± 553 |
| Mn II λ2576           | –555 ± 521 | 73 ± 419  | –658 ± 420 | –488 ± 406 | 150 ± 317 | 322 ± 413 | 1316 ± 578 |
| Fe II λ2249           | –13 ± 747  | –317 ± 1013 | –370 ± 596 | –203 ± 452 | 753 ± 730 | 397 ± 456 | –568 ± 473 |
| Fe II λ2344           | –19 ± 234  | 88 ± 251  | –257 ± 247 | –311 ± 189 | 32 ± 151  | 290 ± 201 | 72 ± 201   |
| Fe II λ2374           | –800 ± 294 | –118 ± 213 | –35 ± 261  | 10 ± 177  | 205 ± 156 | 188 ± 174 | 392 ± 264  |
| Fe II λ2586           | –130 ± 268 | 331 ± 243 | 24 ± 245   | –213 ± 166 | 139 ± 165 | 258 ± 180 | –178 ± 246|
| Si II λ1808           | –20 ± 577  | –619 ± 661 | –1897 ± 719| –497 ± 499 | 241 ± 421 | 612 ± 527 | 1975 ± 768 |
| Weighted mean         | –275      | +70       | –242      | –129      | +142      | +147      | +111      |
| Weighted standard deviation | 357     | 288       | 431       | 374       | 113       | 260       | 561        |
| Weighted standard deviation of all exposures | 170    |

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