CONSTRAINING THE VARIATION OF THE FINE-STRUCTURE CONSTANT WITH OBSERVATIONS OF NARROW QUASAR ABSORPTION LINES*

A. SONGAILA AND L. L. COWIE
Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA; acowie@ifa.hawaii.edu

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ABSTRACT

The unequivocal demonstration of temporal or spatial variability in a fundamental constant of nature would be of enormous significance. Recent attempts to measure the variability of the fine-structure constant $\alpha$ over cosmological time, using high-resolution spectra of high-redshift quasars observed with 10 m class telescopes, have produced conflicting results. We use the many multiplet (MM) method with Mg $\text{II}$ and Fe $\text{II}$ lines on very high signal-to-noise, high-resolution ($R = 72,000$) Keck HIRES spectra of eight narrow quasar absorption systems. We consider both systematic uncertainties in spectrograph wavelength calibration and also velocity offsets introduced by complex velocity structure in even apparently simple and weak narrow lines and analyze their effect on claimed variations in $\alpha$. We find no significant change in $\alpha$, $\Delta \alpha/\alpha = (0.43 \pm 0.34) \times 10^{-5}$, in the redshift range $z = 0.7$–1.5, where this includes both statistical and systematic errors. We also show that the scatter in measurements of $\Delta \alpha/\alpha$ arising from absorption line structure can be considerably larger than assigned statistical errors even for apparently simple and narrow absorption systems. We find a null result of $\Delta \alpha/\alpha = (-0.59 \pm 0.55) \times 10^{-5}$ in a system at $z = 1.7382$ using lines of Cr $\text{II}$, Zn $\text{II}$, and Mn $\text{II}$, whereas using Cr $\text{II}$ and Zn $\text{II}$ lines in a system at $z = 1.6614$ we find a systematic velocity trend that, if interpreted as a shift in $\alpha$, would correspond to $\Delta \alpha/\alpha = (1.88 \pm 0.47) \times 10^{-5}$, where both results include both statistical and systematic errors. This latter result is almost certainly caused by varying ionic abundances in subcomponents of the line; using Mn $\text{II}$, Ni $\text{II}$, and Cr $\text{II}$ in the analysis changes the result to $\Delta \alpha/\alpha = (-0.47 \pm 0.53) \times 10^{-5}$. Combining the Mg $\text{II}$ and Fe $\text{II}$ results with estimates based on Mn $\text{II}$, Ni $\text{II}$, and Cr $\text{II}$ gives $\Delta \alpha/\alpha = (-0.01 \pm 0.26) \times 10^{-5}$. We conclude that spectroscopic measurements of quasar absorption lines are not yet capable of unambiguously detecting variation in $\alpha$ using the MM method.

Key words: atomic data – cosmological parameters – instrumentation: spectrographs – quasars: absorption lines

Online-only material: color figures

1. INTRODUCTION

There has been much interest over the last decade in the possibility that fundamental dimensionless constants may evolve or in some way be a product of the history of the region in which they lie (Uzan 2003). In the case of the fine-structure constant, $\alpha$, one group has claimed to see such time variation (Murphy et al. 2003a, 2003b, 2004; Webb et al. 2003) and spatial variation (Webb et al. 2011, 2014; King et al. 2012) using the “many multiplet” (MM) method of analyzing quasar absorption line spectra, which they pioneered (Webb et al. 1999; Dzuba et al. 1999a, 1999b). However, this positive result is limited to one group and more stringent null results, using the same methodology, have been reported (Srianand et al. 2004; Chand et al. 2004, 2006; Levshakov et al. 2006; Molaro et al. 2013). The early results have been criticized by Murphy et al. (2008a, 2008b) who claim that their quoted significance is too high though not, in the case of the Chand et al. (2004, 2006) result, consistent with evidence for varying $\alpha$ (Srianand et al. 2007; Murphy et al. 2008a). Investigations of the change in $\alpha$ by comparing redshifted radio lines also do not show evidence of time variation (e.g., Cowie & Songaila 1995; Carilli et al. 2000; Kanekar et al. 2010, 2012; Levshakov et al. 2012). These results provide an alternative source of evidence for a non-varying $\alpha$ that has different systematic effects compared to the MM method, though the interpretation depends on assuming a low value for the change in $\mu = m_e/m_p$ for which there is direct evidence at $z < 0.9$ (Kanekar 2011; Bagdonaite et al. 2013a, 2013b); see, e.g., Rahmani et al. (2013) for a summary of results at higher redshift. The discrepancy in published results could be reconciled if systematic effects dominate the measurements, leading to underestimates of the errors. In the present paper we consider both systematic uncertainties in spectrograph wavelength calibration and also velocity offsets introduced by complex velocity structure in even apparently simple and weak narrow lines and analyze their effect on claimed variations in $\alpha$.

The current observational situation regarding variation in $\alpha$ is far from clear. Terrestrial laboratory and geophysical measurements show no sign of any time variation on both long and short timescales. Laboratory measurements (e.g., Uzan 2003) of the stability of atomic clocks are consistent with no instantaneous time variation at the present time, while analysis of the OKLO natural fission reactor places a limit of $-0.11 \leq \Delta \alpha/\alpha \leq 0.24 \times 10^{-7}$ over a time span of 2 Gyr (Gould et al. 2006). Astronomical measurements, on the other hand, have so far given both null results and also the first reported detections of variation. A number of groups have looked for variation in $\alpha$ over cosmic time in quasar absorption lines at high redshift using various methodologies. All such measurements based on comparing the relative wavelength separation of the two members of an alkaline doublet observed at high redshift in a quasar absorption system (Savedoff 1956) are consistent with no evolution (Potekhin & Varshalovich 1994; Cowie & Songaila 1995; Varshalovich et al. 1996; Murphy et al. 2001; Chand et al. 2005). It was only with the advent of the more sensitive MM method (Webb et al. 1999; Dzuba et al. 1999a, 1999b) that a

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significant change at the level of $\Delta \alpha/\alpha = (-0.57 \pm 0.11) \times 10^{-5}$ was claimed over the redshift range $0.2 < z < 4.2$ (Murphy et al. 2004).

The enormous advantage of the MM method is its sensitivity: it is sensitive to $\alpha^{-1} \Delta \alpha$ at a level of about $10^{-5}$ in an individual quasar absorption line system, making it about an order of magnitude better than the alkaline doublet method. On the other hand, this sensitivity is bought at the price of much greater required control of systematic effects, among the most important of which are the accuracy of the wavelength calibrations in the echelle spectrographs being used for the measurements, and the assumptions of uniform velocity structure in the various ion species being compared and uniform spatial abundance patterns (Bahcall et al. 2004; Uzan 2003; Lopez et al. 2002; Prochaska 2003; Rodríguez et al. 2006). The wavelength calibration is particularly critical since, in contrast to the alkaline doublet method, the lines being compared in the MM method can have wide wavelength separations. While these systematic effects have been extensively investigated and modeled (Murphy et al. 2003b, 2004), it is still likely that they do in fact dominate the measurement error and are responsible for the discrepancies in published results.

A suitable choice of ionic species can minimize or exclude some of the potential systematic errors associated with the MM method. In particular, concerns about systematics in the wavelength calibration can be reduced by using lines of singly ionized Cr and Zn to measure individual offsets since these lines are neighboring and interspersed with one another (Figure 1). Since the effect of a change in $\alpha$ is large and in the opposite sense for the two species (Dzuba et al. 2002), these two ions also provide an optimally sensitive measurement. For the neighboring Cr $\equiv$ 2026 Å and the Zn $\equiv$ 2026 Å lines, a change of $\Delta \alpha/\alpha = 10^{-5}$ produces a relative offset of 0.48 km s$^{-1}$ (Dzuba et al. 2002). This is large enough that with a simple sharp absorption line we can hope to measure the offset directly. A crucially important estimate of the magnitude of systematic errors in the MM method comes from having the required sensitivity and spectral resolution to fully analyze a single system at one redshift and map the velocity shifts from ion to ion (Levshakov et al. 2006). This is what we do here for two such systems, at $z = 1.7382$ in the quasar HS1946+7658 and at $z = 1.6614$ in the quasar HE1104−1805A.

However, suitable Cr and Zn systems are rare and most of the MM measurements have been made using Fe $\equiv$ and Mg $\equiv$ lines, which have two disadvantages. First, the offset between Fe $\equiv$ 2600 Å and 2342 Å and the Mg $\equiv$ 2800 Å doublet is smaller (0.21 km s$^{-1}$ for $\Delta \alpha/\alpha = 10^{-5}$) than for the Cr and Zn lines; and second, these systems have a much wider wavelength separation.

We shall show here that it is extremely hard using the HIRES spectrograph on the Keck I Telescope to obtain the necessary wavelength accuracy for this type of measurement.

2. DATA AND DATA REDUCTION

For the present study we chose three quasars from our existing data base of high-resolution quasar spectra (Songaila 2005), which appeared optimal for measuring the fine-structure variation. These are HE1104−1805A ($z_{em} = 2.31$), HS1700+6416 ($z_{em} = 2.73$), and HS1946+7658 ($z_{em} = 3.02$). These three quasars are very bright, allowing us to obtain high signal-to-noise observations even at very high spectral resolution ($R = 72,000$) and their spectra all contain narrow, strong (but not saturated) Mg $\equiv$ lines with corresponding strong Fe $\equiv$. In addition HE1104−1805A and HS1946+7658 contain damped Ly $\alpha$ (DLA) absorbers with simple sharp and unsaturated metal lines that are ideal for measuring the fine-structure variation with multiple lines and, in particular, Zn $\equiv$ and Cr $\equiv$. HE1104−1805 is a gravitationally lensed system with multiple images (Wisotzki et al. 1993), of which the brightest (image “A”) is extremely luminous. The $z = 1.6614$ DLA absorber has intermediate strength Cr $\equiv$ and Zn $\equiv$ lines in its spectrum ($N(Cr \equiv) \sim 7 \times 10^{12}$ cm$^{-2}$ and $N(Zn \equiv) \sim 2.4 \times 10^{12}$ cm$^{-2}$; Figure 1). Furthermore, the dominant feature in the weaker singly ionized absorption lines of the $z = 1.6614$ system is extremely sharp ($b \sim 4$ km s$^{-1}$) and was only marginally resolved in our earlier moderately high-resolution ($R = 35,000$) observations. These earlier observations already suggested there was a velocity offset between the Cr $\equiv$ and Zn $\equiv$ lines in this system. HS1946+7658 also has an isolated narrow system corresponding to the DLA absorber at $z = 1.7382$, which is seen in the Cr $\equiv$, Zn $\equiv$, and Mn $\equiv$ lines, although this system is weaker than that in HE1104−1805A and some useful lines lie in the Ly $\alpha$ forest.

The upgrade of the CCDs in the HIRES spectrograph on the Keck I 10 m Telescope in 2004 provided finer pixel sampling and allowed the instrument to achieve proper sampling of the high spectral resolution that could be obtained with narrow slits. We therefore began an intensive observing program on these three quasars using a slit width of 0.57 Å, corresponding to a spectral resolution of $R = 72,000$, in which we paid careful attention to the wavelength calibration. The seeing was generally larger than the slit width so the slit illumination should be uniform. We will discuss this in detail in Section 3. For each observation, 80 or 100 minute exposures were obtained in two 40 or 50 minute segments to allow for processing to remove cosmic rays. ThAr calibration lamps and in some case iodine cell exposures of a white dwarf standard were taken before and after each pair of quasar exposures (i.e., every 80 minutes). The observations are summarized in Table 1. Each quasar was observed in multiple grating settings to provide complete wavelength coverage. This also allowed us to test how reproducible wavelengths were in
different configurations of the instrument. The total exposure times are 340 minutes for HE1104−1805A, 280 minutes for HS1700+6416, and 600 minutes for HS1946+7658.

The observations were obtained with a two-point binning in the spatial direction (corresponding to a binned pixel size of 0′′.24) and no binning in the spectral direction. Each spectrum was extracted by order using an IDL procedure written for the purpose. The images were initially flattened using normalized exposures of a quartz flat lamp observed in the same spectrograph configuration. In each order the spatial distortion of the spectrum was measured from white dwarf calibration stars taken in the same configuration; these were also used to remove the blaze function of the instrument. Sky subtraction was performed by interpolating the sky measured on each side of the spectrum and a vector corresponding to the sky level at the position of the spectrum was stored for each order. Each spectrum was then extracted using a five-binned spatial pixel window centered on the distorted spatial position at that wavelength to obtain the total counts at that position. Cosmic rays were rejected by comparing the spectra corresponding to the sub-exposures and a final summation of the spectra and the corresponding sky was then made and stored. The ThAr calibration spectrum was then extracted using a five-binned spatial pixel assuming a read noise of six electrons per pixel and a gain setting of 2.4. The final spectral resolution was measured from white dwarf calibration stars such as Mg ii and Fe ii are being used, and requires the adoption of very careful observing techniques and attention to systematics. This has previously been discussed for the HIRES spectrograph by Griest et al. (2010), who used iodine cell exposures to evaluate the systematics of ThAr lamp calibration techniques, and Thompson et al. (2009), who presented a calibration procedure for the Very Large Telescope/Ultraviolet and Visual Echelle Spectrograph (VLT/UVES) spectrograph that removes systematics previously noted in the pipeline procedure by Murphy et al. (2007). To obtain the wavelength calibration, we made ThAr lamp exposures before and after each object exposure, and also took a number of exposures each night of white dwarf standards with the iodine cell in place. Since Griest et al. have made a thorough study of the iodine cell calibration, we will not discuss this issue any further here but concentrate on how well the calibration can be made using only ThAr lines. It should be noted that many of the archival observations used in previous analyses of the variation in the fine-structure constant did not aim for precision calibration. The present discussion relates to observations specifically designed to obtain the most accurate calibrations possible with the ThAr lamp. We first discuss the drift in wavelength calibration exhibited by the before and after ThAr lamp spectra and then analyze the accuracy of the best possible ThAr calibrations using night sky lines that are present in the object spectra and also using the multiple measurements of the various lines furnished by the independent observations, and we compare velocities of doublets seen in the spectra.

3. WAVELENGTH CALIBRATION

The accuracy of the wavelength calibration is a crucial constraint in achieving the sensitivity necessary to measure evolution in the fundamental constants, particularly if widely separated lines such as Mg ii and Fe ii are being used, and requires the adoption of very careful observing techniques and attention to systematics. This has previously been discussed for the HIRES spectrograph by Griest et al. (2010), who used iodine cell exposures to evaluate the systematics of ThAr lamp calibration techniques, and Thompson et al. (2009), who presented a calibration procedure for the Very Large Telescope/Ultraviolet and Visual Echelle Spectrograph (VLT/UVES) spectrograph that removes systematics previously noted in the pipeline procedure by Murphy et al. (2007). To obtain the wavelength calibration, we made ThAr lamp exposures before and after each object exposure, and also took a number of exposures each night of white dwarf standards with the iodine cell in place. Since Griest et al. have made a thorough study of the iodine cell calibration, we will not discuss this issue any further here but concentrate on how well the calibration can be made using only ThAr lines. It should be noted that many of the archival observations used in previous analyses of the variation in the fine-structure constant did not aim for precision calibration. The present discussion relates to observations specifically designed to obtain the most accurate calibrations possible with the ThAr lamp. We first discuss the drift in wavelength calibration exhibited by the before and after ThAr lamp spectra and then analyze the accuracy of the best possible ThAr calibrations using night sky lines that are present in the object spectra and also using the multiple measurements of the various lines furnished by the independent observations, and we compare velocities of doublets seen in the spectra.
Figure 3. Calibration drift as a function of time. In each panel we show the difference in wavelength between the ThAr lines measured before and after the object exposure. Each point shows the directly measured offset of a single ThAr line with the orders color coded by wavelength from longest wavelengths (red) through intermediate wavelengths (green) to the shortest wavelengths (blue). The drift in offset continues smoothly as a function of time (in the first three panels the text shows the time of the second ThAr exposure) resulting in a large offset for the full period of the observations (bottom right panel). The offset is differential with wavelength (see Figure 4) and also shows a gradient along each order.

(A color version of this figure is available in the online journal.)

Figure 4. Average wavelength displacement in each order as a function of the central wavelength of the order. Black squares show data for HS1946+7658, red for HE1104−1805A, and blue for HS1700+6416.

(A color version of this figure is available in the online journal.)

which depends on the relative offset of line pairs. However, the shifts also result in differential offsets along the orders and in the cross-dispersed direction (Figure 3). The relative offset of the orders as a function of wavelength is shown in Figure 4 for all of our ThAr pairs. Both negative and positive absolute offsets are seen and the corresponding gradient is linearly related to the absolute offsets as \( d(\delta \lambda) / d\lambda \propto 1.5 \times 10^{-6} \delta \lambda \) (6000 Å). Typical end-to-end wavelength shifts are \(~0.0015\) Å along the orders though in the most extreme case the value rises to \(~0.0050\) Å.

Under most conditions these offsets will scatter equally to negative and positive values and contribute only to the systematic errors. However, depending on the cause of the drift and the observer procedure, they could result in systematic effects. For example, if the offset were driven by temperature changes, which are more often negative through the night, and if observers normally take ThAr exposures prior to the on-sky observation, then there could be a systematic shift in \( \Delta \alpha \). However, we assume here that the offsets simply add to the error budget.

The actual errors will depend on the observing procedure, but if we assume that the data are being calibrated with a ThAr exposure taken 80 minutes away from the observation (which may be fairly typical) then we can use the current data to estimate the systematic error. For a system at \( z = 1 \), the dispersion in the measured offset between Fe ii 2344 Å and Mg ii 2800 Å corresponds to an rms error of \( 4.5 \times 10^{-6} \) in \( \Delta \alpha / \alpha \) for an individual measurement.

3.2. Sky Lines

We can also use the night sky lines in the spectra of the quasars to test the accuracy of the final wavelength solution and to check if there are residual distortions in the solution arising from the different optical path followed by the ThAr calibration lamp versus sky objects illuminating the slit. Since we used a very narrow slit (in all cases narrower than the typical seeing) the slit was approximately uniformly illuminated, and the sky lines should provide a good calibration. For our ThAr wavelength scale we used the average of the wavelength solutions computed from the before and after ThAr wavelength fits, which should remove much of the drift discussed in the previous subsection.
We selected appropriate night sky lines from the list tabulated by Osterbrock et al. (1996) in the wavelength range 5500–7500 Å. To obtain sufficient accuracy, we recalculated the wavelengths of all lines from the term values in Abrams et al. (1994). We fitted Gaussians to all sky lines using the line-fitting program MPFIT (Markwardt 2009). Examples of the Gaussian fits are shown as the blue solid lines in Figure 5, plotted over the spectrum (black squares and error bars), shown in the observed air wavelength frame corresponding to the ThAr calibration taken immediately before the object exposure. The OH sky lines are doublets owing to Λ-splitting. The theoretical wavelengths of the Λ-split components are shown by the red lines. We fitted Gaussians with the full width of the lines fixed to the measured instrument resolution of $R = 72,000$ and the wavelength offset between the lines fixed to the theoretical separation. Figure 5 shows examples of sky lines with Λ-splitting ranging from just resolved to about four times the instrumental resolution. The offsets of the ThAr-measured wavelengths of the sky lines from the true position range from $10^{-3}$ Å to $7 \times 10^{-3}$ Å. These offsets are significantly larger than the statistical errors expected in the fits, which are typically in the range $5 \times 10^{-4} - 10^{-3}$ Å.

We selected sky lines from this list with intensity $>50$ counts whose Λ-split components are resolved at our instrumental resolution and have roughly equal intensities. We rejected lines whose FWHM from the Gaussian fit appeared to be too narrow, indicating that the line might be spurious. This selection provided 20–30 sky lines in each spectrum.

Figure 6 shows the measured offsets in km s$^{-1}$ for these sky lines in all the spectra as a function of wavelength. The offset is measured from the wavelength position expected from the final wavelength solution, as described above. The black squares with error bars show the individual offsets, the red triangles show the average offset in cases with four or more observations of a given sky line, and the blue diamonds show the offsets averaged in 500 Å bins. The solid line is a linear fit to all the points. Over the range 5500–7500 Å, where there are large numbers of sky lines, we find that there is a significant gradient, with $d(\Delta v)/d\lambda = (-2.91 \pm 0.66) \times 10^{-5}$ km s$^{-1}$ Å$^{-1}$. At $z = 1.5$, using Fe II 2344 Å and Mg II 2800 Å, this would result in an offset in the $\Delta \alpha/\alpha$ measurement of $-1.7 \times 10^{-6}$, a significant correction to measured offsets. Therefore a measurement of $\Delta \alpha/\alpha$ with HIRES using Fe II and Mg II lines and ThAr calibration will show a negative bias. Griest et al. (2010) have also found large systematic errors in the HIRES wavelength calibration between 5000 Å and 6000 Å, using the iodine cell to track wavelength shifts, and Whitmore et al. (2010), using similar methods, report similar though smaller systematics for the...
VLT/UVES spectrograph. By comparing solar and asteroid spectra, Rahmani et al. (2013) found wavelength-dependent offsets for UVES, though with the opposite slope to our result for HIRES.

In what follows we used the average ThAr line measurement for the wavelength solution. In Section 5 we then apply the correction to the wavelength solution based on the sky line fits to correct the measured results so that we can see the comparative size of the effect. The wavelengths were then converted to vacuum heliocentric, which is used, except where specified otherwise, in the subsequent text.

3.3. Testing the Measurement Errors

Error estimation for both Voigt fitting and cross-correlation is complex and there is considerable room for systematic effects. It is our assessment that many of the previous analyses have assigned surprisingly, and possibly unrealistically, small errors to their results. We estimated errors on our fitting in three ways. In the first, we measured the scatter in an individual order using measurements of doublets in the spectra. In the third, we placed the fitted model for a given line at a large number of neighboring random positions in the spectrum and then profile-fitted these simulated lines.

The formal statistical error will not include systematics, such as relative errors in the wavelength determination, uncertainties in the absorption line template, and so on. We therefore refitted the lines, separating the data by night of observation, and also separating systems that appeared in more than one order of the echelle spectrum. A comparison of the individual observations for a Mn II absorption line in HS1946+7658 with the final combined profile is shown in Figure 7. Up to eight independent measurements of the offsets were obtained in this way for some of the absorption lines, and these can be used to make an independent error estimate that should include nearly all of the these random systematic effects associated with the wavelength calibration and profile fitting (though not systematic effects that are present in all the observations such as the linear offset from the ThAr line calibration noted in the previous section).

In Figure 8 we show an example of the measured velocity offsets in a single system relative to the value measured in the combined spectrum. We show the Mg II doublet (black squares) and the Fe II 2344, 2382, and 2600 lines as colored symbols. For the weaker Fe II lines, with their higher statistical errors, the measured dispersion is fully consistent with the statistical error. However for the strong Mg II lines the statistical error is small and is dominated by the systematic error which is approximately 0.1 km s⁻¹ in each individual measurement. This has little effect on any of the measurements discussed in the next sections since the differential errors are always dominated by weaker lines.

Griest et al.’s (2010) iodine cell observations suggest that much of the velocity uncertainty of the ThAr calibration
arises in individual orders (the sawtooth pattern seen in their Figure 4). This is of considerable interest for methods such as the comparison of Cr and Zn lines discussed in Section 4. We therefore tested this by measuring the doublet separations of C\textsc{iv}, Si\textsc{iv}, Mg\textsc{ii}, and Cr\textsc{ii} lines in our data. We used only lines where both members of the doublet were in a single order, where lines appeared to be a single symmetric component, and where both members of the doublet were strong but unsaturated. We show the measured offsets as a function of the wavelength separation of the doublet at the observed redshift in Figure 9. The highest signal-to-noise ratio (S/N) measurements again show a larger scatter than would be expected based on statistical errors, with a typical maximum error of ~0.3 km s\(^{-1}\), consistent with the value expected from the Griest et al. result. This error is expected to be random and should average out with a large enough number of measurements. The systematic error contributes a dispersion of about 0.17 km s\(^{-1}\) in addition to the statistical error, which is large enough to substantially increase the error estimates.

The simulation technique, which was also used by Chand et al. (2004), has the advantage of automatically including the effects of continuum fitting and line contamination in the spectrum as well as the effects of non-Gaussian noise, and is therefore considerably superior in these respects to estimates that rely on only the local statistical noise to estimate the error. We expect a priori that this method will produce a larger estimate of the noise because of these effects. It also allows us to quantify the fraction of times a line will suffer a major error because of contamination by another absorption line feature or other structures in the spectrum. We find that this type of analysis gives an average increase in the noise by a factor of 1.17 over the formal statistical errors, with a range of 0.9–1.3. This is slightly smaller than the factor of 1.5 seen by Agafonova et al. (2011). Most contamination by other lines is easily recognized and would be excluded in the actual measurements, but significant velocity offsets (>4\(\sigma\)) that would not be easily recognized are seen in about 1% of the simulated lines.

4. Cr\textsc{ii}, Zn\textsc{ii}, AND Mn\textsc{ii} MEASUREMENTS

As we have discussed above, measurements based on the Cr\textsc{ii}, Zn\textsc{ii}, and Mn\textsc{ii} lines can avoid some of the wavelength calibration problems, although they are still subject to the in-order errors. However, as we discuss here, variability in relative abundances in the substructure of the line can cause serious problems in analyzing even apparently weak and simple systems. A portion of the spectrum of HE1104–1805A covering the Zn\textsc{ii} and Cr\textsc{ii} lines of interest in an absorption system at \(z = 1.6614\) is shown in Figure 1 and an expanded region around the Cr\textsc{ii} 2062.236 and Zn\textsc{ii} 2062.660 lines is shown in Figure 10. The expanded spectrum demonstrates that the wavelength structure of this absorption is indeed very simple in the weaker singly ionized lines and consists of a single sharp feature that is only marginally resolved, together with very weak broader absorption to the red, which extends only to about 50 km s\(^{-1}\) and is nearly fully separated from the sharp feature. It is the sharp singly ionized line which we focus on here. The velocity offset between the Cr\textsc{ii} and Zn\textsc{ii} lines can already be seen by visual inspection of Figure 10.

We first fitted Voigt profiles to all of the useful singly ionized lines that were not saturated. We used our own customized IDL routines, based on the MPFIT programs of Markwardt (2009). (We note that a cross-correlation analysis gives basically identical results) A two-component fit based on the strong Si\textsc{ii} 1808 line was used. The principal component, containing the bulk of the material, is the narrow feature with a \(b\)-value of 4.1 km s\(^{-1}\); a single broad component was used to model the weaker red wing. We fitted each of the lines by holding the \(b\)-values fixed but allowing the column densities of all the components, and the overall velocity, to vary. The redshifts of the sharp component were measured and the corresponding velocity offsets determined. The offsets are not sensitive at any significant level to the choice of cloud model, and the results are almost unchanged if we allow the column density, velocity, and \(b\)-value to vary independently in the two components. We note that the velocities are consistent between independent measurements of a given ion, suggesting that line contamination and line saturation are not problems.
of the lines. If we include only the Zn
measured the offset that would be obtained from restricted subsets
of (1.87 ± 0.24) × 10⁻⁵. The dashed line shows the null result of Δα/α = (−0.43 ± 0.24) × 10⁻⁵, obtained by including only the Mn ii, Ni ii, and Cr ii lines. Wavelengths are from the compilation of Murphy & Berengut (2014). The unit shift is the displacement in velocity that would be produced by a change in
velocity of the system in HE1104−1805A in Figure 13(a). A linear regression analysis gives (0.74 ± 0.20) × 10⁻⁵ (statistical error only) for the required Δα/α. The best fit is shown by the solid line in the figure. However, the fit has a very poor χ² because of the offset between the Mn ii and Zn ii lines. We have also measured the offset that would be obtained from restricted subsets of the lines. If we include only the Zn ii and Cr ii lines we obtain (1.87 ± 0.24) × 10⁻⁵, whereas if we use the Mn ii, Ni ii, and Cr ii lines this reduces to a null result of (−0.43 ± 0.24) × 10⁻⁵. Including the systematic errors discussed in Griest et al. (2010) and Section 3.3 would significantly increase the errors from 0.24 × 10⁻⁵ to 0.46 × 10⁻⁵ but still leave a highly significant difference between the fits based on the Zn ii and Mn ii lines.

This result shows that there can be serious systematic problems in determining Δα using measurements of just Cr ii and Zn ii. It strongly suggests that, even in a very simple narrow system like the present one, abundance variation in substructure in the sharp feature (the most likely systematic) can produce an apparent offset between the species. Zn and Cr are well known to have very different abundance patterns, an effect that has traditionally been ascribed to dust depletion but may also reflect variations in nucleosynthesis (Pettini 2001; Prochaska 2003). If a positive subcomponent of the narrow absorption line had a high Cr/Zn ratio relative to a negative subcomponent this could pull the relative offsets of Zn ii and Cr ii to negative values. This is consistent with the observed velocity pattern: the weakly refractory Zn ii and Si ii have the most negative velocities, shown by the filled symbols in Figure 11(a), while the refractory elements (Ni ii, Mn ii, Cr ii, and Fe ii) have more positive consistent velocities. It appears that using Mn ii with Cr ii is more secure than using Zn ii with Cr ii since both Mn ii and Cr ii are refractory elements.

Changes in the isotopic mix are unlikely to produce significant changes in the results. The isotopic effect may be largest in the Zn ii lines but even here the maximum shift which could be obtained by changing the isotope mix from the local uniform mix of isotopes to being predominantly ⁶⁴Zn is only about 0.1 km s⁻¹, which is small compared with the measured shifts.

As long as ⁵²Cr remains the dominant isotope we expect the Cr ii lines to have relatively small isotopic shifts (Murphy & Berengut 2014).

The z = 1.7382 system has a very similar structure and we adopted the same fitting procedure. The measured offsets shown in Figure 11(b) yield a consistent solution for both Zn ii and Mn ii relative to Cr ii, albeit with larger errors for this weaker system. The regression analysis gives Δα/α = (−0.94 ± 0.24) × 10⁻⁵ (solid line), while fitting only Zn ii and Cr ii gives Δα/α = (−0.24 ± 0.69) × 10⁻⁵ (dotted line), and fitting only Mn ii and Cr ii gives Δα/α = (−0.96 ± 0.32) × 10⁻⁵ (dashed line).

We show the relation between the offset expected from a change in α and the measured velocity offset for the z = 1.6614 system in HE1104−1805A in Figure 11(a). A linear regression analysis gives (0.74 ± 0.20) × 10⁻⁵ (statistical error only) for the required Δα/α. The dotted line shows the fit obtained by including only the Zn ii and Cr ii lines, giving Δα/α of (1.87 ± 0.24) × 10⁻⁵. The dotted line shows the null result of Δα/α = (−0.43 ± 0.24) × 10⁻⁵, obtained by including only the Mn ii, Ni ii, and Cr ii lines. Wavelengths are from the compilation of Murphy & Berengut (2014). The unit shift is the displacement in velocity that would be produced by a change in velocity of the system in HE1104−1805A and Δα/α = (−0.47 ± 0.53) × 10⁻⁵ for the z = 1.6614 system in HE1104−1805A and Δα/α = (−0.79 ± 0.62) × 10⁻⁵ for the z = 1.7382 system in HS1946+7658. However, systematic errors remain a concern even when using the more consistent ions and in particular abundance variations may cause velocity shifts. Large numbers of systems would be required to average out the latter effect.

5. Mg ii MEASUREMENTS

We next analyzed the eight narrow Mg ii absorption systems seen in the three quasars. These are drawn from five independent complexes, two of which contain two or three useful isolated narrow features. The Fe ii and Mg ii lines in each of the systems are shown in Figure 12. In all cases the lines are separated from neighboring absorption features and at least some of the Fe ii lines are strong enough for accurate measurements. The Mg ii doublet ratio can be used to estimate the degree of saturation, and there are four systems in which the Mg ii lines appear unsaturated and four in which at least the Mg ii lines show saturation effects. We profile-fitted each of the lines using a model based on the Mg ii 2803 line and varying only the individual column densities of the components and the overall velocity of the system. The results are shown in Figure 13.

Figure 13 shows that the spread of these systems, which range in redshift from z = 0.7 to z = 1.5, is consistent
with the assigned errors. Including only statistical errors, the error-weighted $\Delta \alpha/\alpha$ is $(0.10 \pm 0.24) \times 10^{-5}$. When we correct for the wavelength bias discussed in Section 3.2 and for the systematic errors discussed in Section 3.3 this becomes $\Delta \alpha/\alpha = (0.43 \pm 0.34) \times 10^{-5}$. The small offsets for Mg II relative to Fe II also show that change in the isotopic mix of Mg II from the local value is not large in these systems and is not weighted toward the heavier isotopes. However, the effects of the isotopic mix in some of the quasar absorption lines can be large (Agafonova et al. 2011) and could contribute to the spread seen here.

6. SUMMARY

MM measurements of the evolution of the fine-structure constant are generally based on either comparison of Mg II and Fe II lines or (at higher redshifts) on measurements of Cr II, Zn II, Ni II, and Mn II lines. Both have significant problems which have to be dealt with in order to obtain an accurate limit.
measurements of $\Delta \alpha/\alpha = (0.01 \pm 0.26) \times 10^{-5}$. We conclude that spectroscopic measurements, made using these methods, are not yet capable of unambiguously detecting variation in $\alpha$.

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