

# Accurate laboratory wavelengths of some ultraviolet lines of Cr, Zn and Ni relevant to time variations of the fine structure constant

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## ABSTRACT

The quality of astronomical spectroscopic data now available is so high that interpretation and analysis are often limited by the uncertainties of the laboratory data base. In particular, the limit with which space–time variations in the fine structure constant  $\alpha$  can be constrained using quasar spectra depends on the availability of more accurate laboratory rest wavelengths. We recently measured some transitions in magnesium by high-resolution Fourier transform spectroscopy for this purpose, and we now report measurements on some ultraviolet resonance lines of Zn II (2062 and 2026 Å), Cr II (2066, 2062 and 2056 Å) and Ni II (1751, 1741, 1709 and 1703 Å). Apart from the last line, which is very weak, the uncertainty of these measurements is  $0.002 \text{ cm}^{-1}$  ( $0.08 \text{ mÅ}$ ) for the lines around 2000 Å and  $0.004 \text{ cm}^{-1}$  ( $0.12 \text{ mÅ}$ ) for the lines around 1700 Å.

**Key words:** atomic data – line: profiles – methods: laboratory – techniques: spectroscopic – quasars: absorption lines – ultraviolet: general.

## 1 INTRODUCTION

Echelle spectroscopy of high-redshift quasars provides a high-precision technique for studying the physics of the young universe. The quality of the observational data is now so high that the limits on measurement accuracy are set by the precision of the available laboratory data. For example, redshifts of two of the Ni II transitions for which we report measurements in this paper, seen in the spectrum of the quasar GB1759+7539, have been attributed statistical uncertainties of  $3 \times 10^{-6}$  (e.g. Outram et al. 1999). This corresponds to an uncertainty in the rest wavelength of 1.4 mÅ. However, the laboratory wavelengths used to derive those redshifts were known to a precision of only 2 mÅ (Morton 1991).

The astrophysical application that motivates the measurements we describe here is a search for any space–time variation in the fine structure constant,  $\alpha$ , where  $\alpha = (1/\hbar c)(e^2/4\pi\epsilon_0)$ . Kaluza–Klein and higher dimensional unification theories such as string theories require the presence of additional dimensions (other than the usual 3+1), ‘compactified’ on small scales. In these models, the values of the fundamental constants are linked to the scalelengths of the extra dimensions. Any cosmological evolution in these

scalelengths may be revealed through a change in the values of the constants (Marciano 1984; Barrow 1987). Another potential source of variation of fundamental constants is associated with temporal and spatial evolution of a dilaton field, generic to all superstring theories (Damour & Polyakov 1994).

At present, no mechanism for *preventing* evolution of the additional dimensions is known. Static cosmological models are also, in general, rather contrived. Indeed, one has to introduce unusual behaviours of a cosmological scalar field in order to prevent unified theories from predicting time-dependent gauge coupling constants (Damour & Polyakov 1994; Fujii, Omote & Nishioka 1994) (reminiscent of Einstein’s motivation for introducing the cosmological constant, yielding only a pseudo-static universe).

Varying speed of light models have received much recent attention, and provide another form of expressing varying  $\alpha$  (Clayton & Moffat 1999; Barrow & Magueijo 1999). It is interesting to note that varying  $\alpha$  may be able to explain the supernovae results for a non-zero cosmological constant  $\Lambda$  (Barrow & Magueijo 2000). These theories may also solve other cosmological problems (e.g. the horizon, flatness, monopole problems) (Barrow & Magueijo 1998; Albrecht & Magueijo 1999).

The ratio of the fine structure splitting to the mean transition frequency in a simple spectrum such as an alkali-type doublet is proportional to  $\alpha^2$ . Therefore, a test for the variation of  $\alpha$  is to

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compare this ratio in quasar spectra with the laboratory value. The precision achievable from this test has been limited by the quality of the quasar spectra, the accuracy of the laboratory wavelengths, and the constant of proportionality linking the frequency shift and  $\alpha^2$  for the particular species examined.

In fact, the relativistic corrections to all atomic transition frequencies (not just alkali-type doublets) are also proportional to  $\alpha^2$  (to first order), but the idea was previously restricted to using alkali doublets alone because of the complexity in computing the proportionality constants for more complex species. However, recent relativistic many-body calculations (Dzuba, Flambaum & Webb 1999a,b) have shown that a dramatically increased sensitivity to variation of  $\alpha$  can be obtained by comparing suitably chosen species, since both the magnitude and the direction of the correction can vary from one atom or ion to another and from one transition to another within the same species (Webb et al. 1999). The resonance lines of Zn II, Cr II and Ni II are of particular interest in this respect because these species are commonly observed in damped Lyman-alpha absorption systems and because they span a wide dynamic range in proportionality coefficients and exhibit both negative and positive shifts.

In this paper we describe the results of experiments at both Imperial College (IC) and Lund University (LU) to measure accurately the wavelengths of these Zn, Cr and Ni lines, together with a confirmation at LU of the earlier measurements on Mg at IC (Pickering, Thorne & Webb, 1998). Although the measurements in the two laboratories were made independently, they used similar high resolution UV Fourier transform (FT) spectrometers, with hollow cathode lamps as light sources. The measurement precision for a single resolved line is determined by its signal-to-noise ratio, but the absolute accuracy depends also on the wavenumber calibration. The reference wavenumbers used in both laboratories derive from the same set of Ar II lines, via a set of ‘standard’ lines in the spectrum of Fe II (Nave et al. 1991) that were also used to calibrate the Mg lines in the earlier paper.

## 2 EXPERIMENTAL METHOD

The wavelengths were measured by Fourier transform spectrometry (FTS), using the two UV FT instruments at IC (Thorne et al. 1987) and a similar instrument at LU. The resolution, between 0.05 and 0.065  $\text{cm}^{-1}$  above 2000  $\text{\AA}$  and 0.08  $\text{cm}^{-1}$  below, was sufficient to resolve the lines fully. Sufficient scans were co-added to achieve signal-to-noise ratios of more than 200 except for the Ni II lines (see detailed results below).

Both laboratories used hollow cathode discharge lamps as sources, with cathodes about 8 mm in diameter and 35 mm long. Ar or Ne was the carrier gas, and currents ranged from 150 to 600 mA. At Lund a ‘composite’ cathode was made by placing small pieces of Mg, Cr and Zn in a pure Fe cathode so that all four spectra were recorded simultaneously. At IC the Zn spectrum was excited in a similar way (a small piece of Zn in a stainless steel cathode), but the Cr and Ni spectra were obtained from cathodes made of pure Cr and Ni, respectively. (Mg in a Ni cathode was used for the earlier IC experiment). At high currents and/or with anything more than a trace of zinc in the cathode, the resonance doublet of Zn II is significantly self-absorbed. In both laboratories, runs were taken at different currents and vapour density to reduce the self-absorption. The effects of the residual self-absorption are discussed in Section 3 below.

In FTS the noise (predominantly photon noise in our case) is transformed along with the spectrum, and white noise is distributed uniformly through the spectrum. Thus every line seen by the detector contributes to the noise at every point in the spectrum, and it is disadvantageous to record lines outside the region of interest. The spectra above 2000  $\text{\AA}$  were recorded with solar-blind photomultipliers (R166), which have a long-wavelength cut-off at about 3000  $\text{\AA}$ . Although the interferometers themselves are evacuated, the air path between the source and the interferometer imposed an effective short-wavelength limit of about 1900  $\text{\AA}$ . The Ni II lines below 1800  $\text{\AA}$  were recorded with a R1259 photomultiplier, which has a cut-off at about 1850  $\text{\AA}$ , and auxiliary spectra were taken to provide the wavelength calibration as described in Section 3. These VUV spectra are beyond the range of the LU spectrometer and were taken at IC only.

## 3 ANALYSIS AND RESULTS

### 3.1 Wavenumber calibration

The wavenumber scale of an FT spectrum derives from the stabilised He–Ne laser that is used to determine the sampling intervals for the interferogram, and it is accurately linear – i.e.  $\sigma_{\text{exp}} = \sigma_0(1 - \epsilon)$ , where  $\sigma_{\text{exp}}$  and  $\sigma_0$  are the observed and true wavenumbers respectively. The ‘stretch factor’  $(1 - \epsilon)$  is due to the finite size of the interferometer entrance aperture and any possible offsets in the angle of the laser beam through the interferometer;  $\epsilon$  is of the order of the reciprocal of the resolving power. In principle a single reference line is sufficient to evaluate  $\epsilon$ . In practice, a number of reference lines are used, and the mean value of  $(\sigma_0 - \sigma_{\text{exp}})/\sigma$  determines  $\epsilon$ . It is *not* necessary to have the reference lines distributed through the spectrum, as is the case for a grating, and the calibration can be carried through from one spectral region to another provided the overlap region contains suitable transfer lines (Learner & Thorne 1988).

In all of these experiments the calibration lines came directly (or, in the case of Ni, indirectly) from the recommended Fe I and Fe II ‘standards’ of Nave et al. (1991), which in turn derive from a selected set of 26 Ar II lines in the blue region (Learner & Thorne 1988), originally measured against the  $^{86}\text{Kr}$  standard by Norlén (1973). A subset of 17 Fe II lines from the list of Nave et al. was used to calibrate the Mg, Cr and Zn lines at LU and the Zn lines at IC. The IC Cr wavelengths were taken from the spectra of J.E. Murray, recorded some 10 yr ago (Murray 1992). Murray used the Fe lines in spectra taken with a stainless steel hollow cathode (70 per cent Fe, 18 per cent Cr, 10 per cent Ni) to calibrate the stronger Cr lines, which then became the reference lines for the pure Cr spectra. The calibration uncertainty of all these lines is estimated to be between 1 and 2 mK, where 1 mK = 0.001  $\text{cm}^{-1}$ .

The calibration of the VUV Ni II spectra presented some difficulties because we were not able to excite simultaneously good (low noise) Fe II and Ni II spectra in this region. A reliable set of Ni I wavelengths down to about 2000  $\text{\AA}$  is available from the work of Litzén, Brault & Thorne (1993), but it was necessary to take further spectra with an R1220 photomultiplier and two different interference filters to bridge satisfactorily the gap between 2000 and 1750  $\text{\AA}$ , in which there are few strong Ni lines. The wavelengths of the reference Ni I lines were obtained from the stainless steel spectra in the same way as those of the Cr lines. We estimate the cumulative calibration uncertainty for the VUV Ni II lines to be 2.5 mK.

### 3.2 Line fitting

The profiles of emission lines, for both neutral and ionic species, generated in a hollow cathode discharge are usually well described by Voigt functions with small damping factors. The line-fitting programs written for FT spectra by Brault (1987) use an iterative least-squares procedure to evaluate the Voigt parameters. For a symmetric isolated line, the uncertainty  $\epsilon$  in the central wavenumber of the fitted Voigt profile is given by (Brault 1987)

$$\epsilon = W/(\sqrt{n} \times \text{SNR}) \quad (1)$$

where  $W$  is the full width at half maximum of the line in the same units as  $\epsilon$ ,  $n$  is the number of independent spectral points across  $W$ , and SNR is the signal-to-noise ratio for the line.

The fitting of the Cr lines is straightforward because any isotope or hyperfine structure should be negligible compared to the Doppler width (Cr has 84 per cent of the even isotope  $^{52}\text{Cr}$ ). The Zn II resonance doublet presents a potential problem because some degree of self-absorption in all the spectra was indicated by the departure of the two components from the theoretical 2:1 intensity ratio. Whereas the centre of a truly symmetric line is not shifted by modest self-absorption, the presence of unresolved isotope structure (Zn has three even isotopes of comparable abundance) might give rise to a small shift. As shown in the next subsection, we believe any such shift to be within the other uncertainties. Ni has two abundant isotopes,  $^{58}\text{Ni}$  at 68 per cent and  $^{60}\text{Ni}$  at 26 per cent, but no asymmetry was observable in the Ni II lines of interest here. As there was also no evidence of self-absorption, the potential problem noted for Zn does not arise for Ni.

The signal-to-noise ratios for the Cr and Zn lines both at LU and at IC lead to wavenumber uncertainties of less than 1 mK, and the results from the two laboratories agree to within this uncertainty. In Table 1 we present the weighted means of the two sets of results. Taking into account the calibration uncertainty that they have in common, we ascribe an absolute uncertainty of 2 mK to these values.

The signal-to-noise ratios for the VUV Ni II lines are significantly poorer. The measurements on two spectra, one taken recently and one nearly 4 yr ago, agree to well within their respective uncertainties, and the weighted means are presented in Table 1. (As these spectra were taken at two different currents, 600 and 200 mA, respectively, this agreement confirms our assumption that any shifts from unresolved isotope structure lie within the

other uncertainties.) For the first three lines the combined measurement and calibration uncertainty is 4 mK, and for the fourth (rather weak) line it is 15 mK.

Fig. 1 shows the line profiles of all the Cr, Zn and Ni lines in Table 1. The intensity scale is set to make the rms noise equal to 1 in each case.

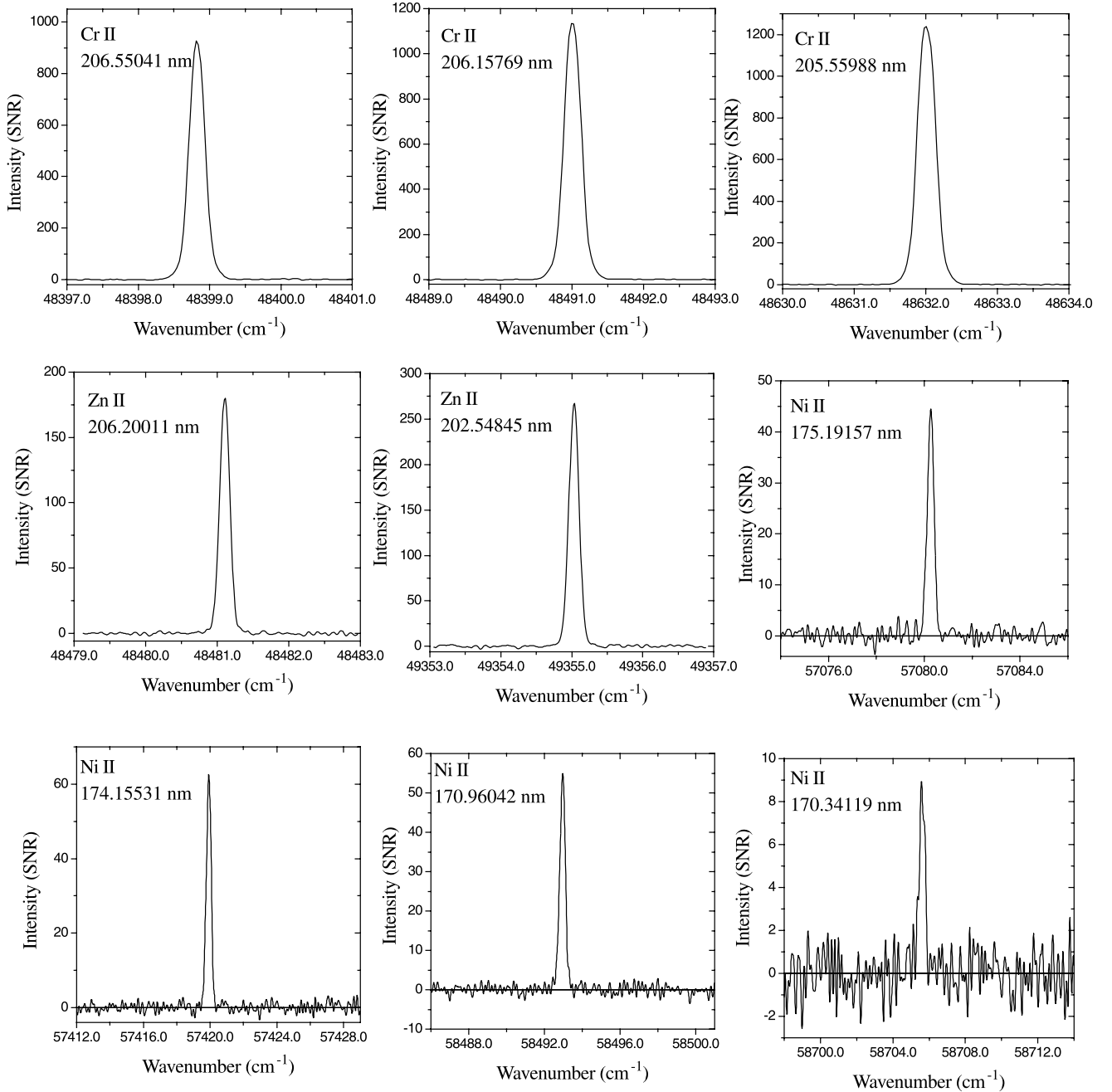
Table 1 also includes the Mg lines previously published from IC (Pickering, Thorne & Webb 1998). The LU measurements of these Mg lines agree within 1 mK, thus providing important confirmation.

### 3.3 The Zn II resonance doublet isotope structure

Zn has three main isotopes, 64, 66 and 68, with abundances 48.6 per cent, 27.9 per cent and 18.8 per cent, respectively. The odd isotope, 67, has an abundance of only 4.1 per cent. There do not appear to be any determinations of the isotope shift for the resonance doublet, but an approximate value can be deduced from the analysis of the measured isotope structure in the 5894 Å line of Zn II given by Foot et al. (1982). This transition,  $3d^{10}4p^2P_{1/2}-3d^94s^2D_{1/2}$ , has a large specific mass shift because of the change in the number of d-electrons. Foot et al. deduce that the field shift, which is due to the two 4s electrons in the upper level, is +24 and +21 mK for the pairs 64–66 and 66–68, respectively. The Zn II resonance doublet, on the other hand, is a 4s–4p transition outside a closed d-shell. The specific mass shift is likely to be negligible, and the field shift due to the 4s electron in the lower state might reasonably be expected to be about half the value for the 5894 line and in the opposite direction – i.e. about –12 and –10 mK for the two isotope pairs. Straightforward evaluation of the normal mass shift gives +12.5 mK for  $\Delta M = 2$  for the 2062 Å line and +12.8 mK for the 2026 Å line. The estimated total separation between isotope pairs is therefore less than +3 mK in both lines. To estimate the effect of self-absorption on a transition with isotope splitting of a few mK, we modelled the line with +10 mK separations between the isotopes, first with relative intensities corresponding to their abundances and then with relative intensities changed to mimic 50 per cent reduction in the intensity of the most abundant. (This reduction is compatible with the observed relative intensities of the two members of the doublet.) The shift found by the line-fitting algorithm was only +1 mK. There is evidence from some of the LU spectra that significantly stronger self-absorption produces a negative shift of

**Table 1.** Wavelengths of Cr, Zn, Ni and Mg resonance lines. Columns 2–4 give the weighted means of the IC and LU results for Cr, Zn and Ni. Column 4 is the value given by Morton (1991). For Mg II the previously published IC measurements are given.

	$\lambda_{\text{air}}$ (Å)	$\lambda_{\text{vac}}$ (Å)	Wavenumber ( $\text{cm}^{-1}$ )	$\lambda_{\text{vac}}$ (Morton 1991) (Å)
Cr II	2065.5041	2066.1640 ± 0.0001	48398.868 ± 0.002	2066.161
Cr II	2061.5769	2062.2361 ± 0.0001	48491.053 ± 0.002	2062.234
Cr II	2055.5988	2056.2569 ± 0.0001	48632.055 ± 0.002	2056.254
Zn II	2062.0011	2062.6604 ± 0.0001	48481.077 ± 0.002	2062.664
Zn II	2025.4845	2026.1371 ± 0.0001	49355.002 ± 0.002	2026.136
Ni II		1751.9157 ± 0.0001	57080.373 ± 0.004	1751.910
Ni II		1741.5531 ± 0.0001	57420.013 ± 0.004	1741.549
Ni II		1709.6042 ± 0.0001	58493.071 ± 0.004	1709.600
Ni II		1703.4119 ± 0.0004	58705.707 ± 0.015	1703.405
Mg I	2852.1251	2852.9631 ± 0.0001	35051.277 ± 0.001	2852.126
Mg II	2795.5301	2796.3543 ± 0.0001	35760.848 ± 0.002	2796.352
Mg II	2802.7056	2803.5315 ± 0.0001	35669.298 ± 0.002	2803.531



**Figure 1.** Observed profiles of the lines reported in this paper. The resolution is a factor of 3–4 times smaller than the line widths, so the line profiles are determined by the Doppler width attributable to the light source.

1–2 mK, suggesting a larger field shift than that estimated above. These strongly self-absorbed lines have not been used in arriving at our final results.

Table 1 sets out our weighted mean values for all the lines, together with the values from Morton’s compilation (Morton 1991), and our previous measurements of Mg. Morton’s values have been given to seven digits because the vacuum wavelengths in his compilation are given to three decimal places of Å corresponding to two decimal places of  $\text{cm}^{-1}$ .

As is frequently the case, most of the actual data are much older – up to 20 yr – than the latest compilation. Morton’s 1991 values for Cr and Ni are taken from Sugar & Corliss (1985). The Cr II energy levels were redetermined by Johansson in 1983 (private

communication to Sugar & Corliss), but the measurements and spectral analysis for Ni II are the work of Shenstone (1970). Sugar & Corliss (1985) estimate the accuracy to be about  $0.05 \text{ cm}^{-1}$ , or 2 mÅ. The Zn II doublet was measured by Martin & Kaufmann (1970) to about the same accuracy.

#### 4 CONCLUSIONS

Motivated by recent advances in spectroscopy of high-redshift gas clouds, we have made accurate laboratory measurements of Cr II, Zn II and Ni II transitions, which are observed in quasar spectra. The importance of the new laboratory wavelengths, in the context

of searches for space–time variation of the fine structure constant  $\alpha$ , is that they can now be incorporated into analyses similar to that of Webb et al. (1999), enabling a reduction of systematic effects. We note also that the new laboratory wavelengths presented here and in our earlier paper will also prove valuable for spectroscopy of stars and the inter-stellar medium, as well as for quasar spectroscopy.

Confidence in the accuracy of the Cr and Zn measurements we report here is increased by the good agreement (within the stated uncertainties) between independent measurements from two laboratories. Some of these measurements extend over many years. The Ni lines were measured only at IC. The IC wavenumbers for the Mg lines reported in our previous paper (Pickering et al. 1998) have also been confirmed at LU. However, it should be noted that the absolute wavenumber scales for the Mg, Cr, Zn and Ni lines, as well as that for the Fe lines given by Nave et al. (1991), all originate from the same set of Ar II reference lines. Any error in the calibration factor derived from these lines will be a systematic multiplicative error in all the IC and LU measurements:  $\Delta\sigma = \epsilon\sigma$  where  $\Delta\sigma$  is the error in the wavenumber  $\sigma$  and  $\epsilon$  is certainly not greater than  $4 \times 10^{-8}$ .

The results of the earlier IC measurements of Fe II (Nave et al. 1991) and Mg II and Mg I (Pickering et al. 1998), combined with new theoretical developments (Dzuba et al. 1999a,b) enabled an order-of-magnitude increase in the precision with which one can constrain changes in  $\alpha$  (Webb et al. 1999). Those particular transitions effectively restrict the maximum observed redshift range to  $\sim 1.5$  or so. At higher redshifts, the redshifted transitions fall at observed wavelengths where emission and absorption features in the sky and atmosphere reduce the reliability of the results. The new IC and LU measurements presented in this paper will now allow that redshift range to be extended to at least  $z \sim 2.5$ , using Ni II, Cr II, Zn II and other transitions of lower rest wavelength.

The fact that the magnitudes of the shifts vary according to the species/transition by at least one order of magnitude, and also that the *direction* of the shift can be of *opposite sign* for a given change in  $\alpha$  (Dzuba et al. 1999a,b), means that transitions with *small* relativistic corrections act as ‘wavelength anchors’, against which shifts in species with larger relativistic corrections can be measured. Large shifts of opposite signs are important in that these will assist in negating systematic uncertainties in the quasar spectra. Comparing results from different species with relativistic corrections of opposite sign *must* yield different inferred variations in  $\alpha$  if systematic errors in the data are significant. If, on the other

hand the comparison yields consistent variations in  $\alpha$ , it would be hard to attribute the results to anything other than a genuine change in  $\alpha$ . Considerations like these strongly motivated the measurements we describe here and will allow an important check on the very tentative indication that  $\alpha$  may actually have varied with time (Webb et al. 1999).

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