Accurate laboratory ultraviolet wavelengths for quasar absorption-line constraints on varying fundamental constants

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Accepted 2006 April 26. Received 2006 April 25; in original form 2005 November 8

ABSTRACT
The most precise method of investigating possible space–time variations of the fine-structure constant, \( \alpha \equiv (1/\bar{c})(e^2/4\pi\epsilon_0) \), using high-redshift quasar absorption lines is the many-multiplet (MM) method. For reliable results this method requires very accurate relative laboratory wavelengths for a number of UV resonance transitions from several different ionic species. For this purpose laboratory wavelengths and wavenumbers of 23 UV lines from Mg I, Mg II, Ti II, Cr II, Mn II, Fe II and Zn II have been measured using high-resolution Fourier transform (FT) spectrometry. The spectra of the different ions (except for one Fe II line, one Mg I line and the Ti II lines) are all measured simultaneously in the same FT spectrometry recording by using a composite hollow cathode as a light source. This decreases the relative uncertainties of all the wavelengths. In addition to any measurement uncertainty, the wavelength uncertainty is determined by that of the Ar II calibration lines, by possible pressure shifts and by illumination effects. The absolute wavenumbers have uncertainties of typically \( \pm 0.001–\pm 0.002 \) cm\(^{-1} \) (\( \Delta \lambda \approx 0.06–0.1 \) mÅ at 2500 Å), while the relative wavenumbers for strong, symmetric lines in the same spectral recording have uncertainties of \( \pm 0.0005 \) cm\(^{-1} \) (\( \Delta \lambda \approx 0.03 \) mÅ at 2500 Å) or better, depending mostly on uncertainties in the line-fitting procedure. This high relative precision greatly reduces the potential for systematic effects in the MM method, while the new Ti II measurements now allow these transitions to be used in MM analyses.

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

1 INTRODUCTION
Ultraviolet (UV) transitions of metallic ions, particularly those involving the ground or low-lying states, are important probes of the interstellar medium (ISM), providing direct information about the abundances and kinematics of gas clouds along the lines-of-sight toward bright stars. The advent of space-borne telescopes equipped with high-resolution UV spectrographs, such as the Goddard High Resolution Spectrograph (GHRS), the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope and the Far Ultraviolet Spectroscopic Explorer (FUSE), focused attention on the (im)precision of most UV resonance laboratory wavelengths (e.g. Morton 1991). Typical laboratory wavelength uncertainties were \( \sim 2 \) mÅ (Morton 1991) while the resolving powers of the astronomical spectrographs were as high as \( R \sim 50 000 \) (25 mÅ at 1250 Å). Thus, the analysis technique and physical information recoverable from the astronomical spectra were often compromised (e.g. Linsky et al. 1995).

The same UV transitions are observed in the optical region in the study of highly redshifted absorption lines arising in galaxies and the intergalactic medium along the sight lines to distant quasars [quasi-stellar objects (QSOs)]. The era of 8–10-m class ground-based telescopes with stable high-resolution spectrographs (e.g. Keck/HIRES, VLT/UVES, Subaru/HDS) has seen a dramatic improvement in the quality and quantity of spectra covering a multitude of metal-line transitions, particularly in studies of damped Lyman \( \alpha \) systems (e.g. Lu et al. 1996; Prochaska, Howk & Wolfe 2003). While it is clearly important for these general Galactic and extragalactic applications to have accurate and precise laboratory wavelengths, recent developments in the study of cosmological variations in the fundamental constants has demanded an order of magnitude improvement in the laboratory wavelengths of several ionized metallic transitions.

The universality and constancy of the laws of nature rely on the space–time invariance of fundamental constants, such as the fine-structure constant, \( \alpha \equiv (1/\bar{c})(e^2/4\pi\epsilon_0) \). Tests of the constancy of

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\( \alpha \) therefore probe deviations from the standard model of particle physics. QSO absorption lines are a particularly attractive probe, constraining \( \alpha \) variation over large spatial and temporal scales. Initial studies (e.g. Bahcall, Sargent & Schmidt 1967; Varshalovich & Potekhin 1994; Cowie & Songaila 1995) focused on comparison of the fine-structure splitting in alkali doublets (ADs) of, for example, Si IV in QSO and laboratory spectra but, as demonstrated by Murphy et al. (2001c), the dominant error in these studies arose from laboratory wavelength uncertainties.

Considerable recent interest has focused on the many-multiplet (MM) method introduced by Dzuba, Flambaum & Webb (1999a,b) and Webb et al. (1999). The MM method is a generalization of the AD method, constraining changes in \( \alpha \) by utilizing many observed transitions from different multiplets and different ions associated with each QSO absorption system. It holds many important advantages over the AD method, including an effective order-of-magnitude precision gain stemming from the large differences in the sensitivity of light (e.g. Mg, Si, Al) and heavy (e.g. Fe, Zn, Cr) ions to varying \( \alpha \). The MM method, applied to Keck/HIRES QSO absorption spectra, has yielded very surprising results, with the first tentative evidence for a varying \( \alpha \) by Webb et al. (1999) becoming stronger with successively larger samples (Murphy et al. 2001a; Webb et al. 2001; Murphy, Webb & Flambaum 2003; Murphy et al. 2004). Although these results have proven robust to many astrophysical and instrumental systematic errors (Murphy et al. 2001b, 2003), more recent studies of much smaller samples of VLT/UVES spectra suggest null results (Chand et al. 2004; Quast, Reimers & Levshakov 2004; Srianand et al. 2004; Levshakov et al. 2005; Chand et al. 2006). The discrepancy between the Keck/HIRES and VLT/UVES results is yet to be resolved.

The precision in the relative change in \( \alpha \) achieved by the above MM analyses is \( \delta(\Delta \alpha/\alpha) \sim 10^{-4} \) which corresponds to a velocity precision of \( \delta v \sim 20 \) m s\(^{-1}\), or \( \delta \lambda \sim 2 \times 10^{-4} \) Å at 2500 Å – a typical rest-frame wavelength for the transitions used in MM analyses. This is an order of magnitude more precise than most lines in Morton (1991). Significant recent effort has therefore been invested into improving the laboratory wavelengths of transitions which can be used in MM analyses.

High precision laboratory measurements of UV lines from Mg I, Mg II, Cr II, Zn II and Ni II have been previously been reported by Pickering, Thorne & Webb (1998) and Pickering et al. (2000). In this paper, we have remeasured these lines [except the Ni II lines, which are beyond the range of the Lund Fourier transform (FT) spectrometer] for confirmation. We have also included another set of lines from Mg I, Ti II, Mn II and Fe II, which are all visible in QSO absorption spectra. In total we present high-precision laboratory wavelength measurements of 23 UV lines from seven ionic species. The uncertainty in the laboratory wavelengths depends both on the measurement precision and the wavelength calibration. To reduce the uncertainty in relative wavelengths, the spectra of all ionic species were produced in the same hollow cathode light source, using a composite cathode. This made it possible for the different spectra to be recorded simultaneously and the relative wavelengths are thus less dependent on the calibration uncertainty. Because of a combination of range in relative line intensities, a line blend, and detector and instrument response at different wavelengths, it was necessary to acquire three different spectra for this analysis. The wavelengths for all lines, apart from one weak Fe II line, are determined with the required uncertainty of \( \pm 2 \times 10^{-4} \) Å or better. For strong symmetric lines measured in the same recording the relative uncertainties are estimated to be \( \pm 0.3 \times 10^{-4} \) Å or better. Confidence in this level of uncertainty was ensured by investigations of calibration effects as well as isotope structure and hyperfine structure of the lines.

### 2 Experimental Method

Spectra of Mg I, Mg II, Ti II, Cr II, Mn II, Fe II and Zn II were produced in a water cooled hollow cathode discharge lamp (HCL). The composite cathode used was made of pure Fe with small pieces of Mg, Ti, Cr, Mn and Zn placed in it. The cathode had an inner diameter of 7.0 mm and a length of 50 mm. A mixture of Ne and Ar was used as carrier gas. Ne generally produces higher signal-to-noise ratios while Ar is used for wavelength calibration. The mixture of about 1/3 Ne and 2/3 Ar gave a stable light source with good signal-to-noise ratios (>100) for most lines used in this study. The light source was run with a current between 0.6 and 0.7 A and a pressure between 0.9 and 1.0 torr. The main excitation mechanism in the hollow cathode is electron collisions, but charge transfer with the carrier gas ions may in certain cases contribute to the production and excitation of singly ionized atoms (Johansson & Litzén 1978). Spectra were also recorded with a pure Fe cathode since the Fe II \( \lambda 2586 \) Å line was blended with a Mn II line in the spectrum from the composite cathode. The Mn II transition in question is not one of interest in QSO absorption-line work – it is between two excited states rather than between the ground (or very low-lying) state and an excited state.

The wavenumbers were measured with the Lund FT500 UV FT spectrometer, which is optimized in the wavelength range of 2000–7000 Å. Spectra of two overlapping wavenumber regions were acquired with different photomultiplier detectors, one between 20 000 and 40 000 cm\(^{-1}\) and another between 25 000 and 50 000 cm\(^{-1}\). It was not possible to include all lines of interest in one recording because of the limitations in wavenumber range for the photomultipliers and the FT spectrometer. The Ti II lines are lower in wavenumber than the rest of the lines and were therefore measured in a separate spectral acquisition. This recording also included the Ar II calibration lines. The resolution of the measurements was 0.06 cm\(^{-1}\) for the measured spectrum between 25 000 and 50 000 cm\(^{-1}\) and 0.05 cm\(^{-1}\) between 20 000 and 40 000 cm\(^{-1}\). This was sufficient to completely resolve the single lines. 20 scans were co-added to achieve good signal-to-noise ratios (>100) for most of the lines in this study.

The noise in spectra observed with FT spectrometry, using the type of light source and detectors stated above, is predominantly photon noise. White noise in the interferogram is transformed into the spectral region as white noise, with a constant level throughout the spectrum. All spectral lines seen by the detector contribute to this noise level. It is therefore a disadvantage to record lines outside the region of interest. In order to band limit the spectra, reducing the noise, solar-blind photomultipliers (Hamamatsu R166) were used for the UV region. These have a long-wavelength cut-off at about 3000 Å. For the lower wavenumber region, UV to visible, a wider range photomultiplier (IP28) was used. The two types of photomultipliers overlap in wavenumber regions, giving a small region for transfer of calibration between them (see Section 3.1).

The light source was placed close to the aperture of the spectrometer and focused with a lens. This was to increase the signal-to-noise ratio for lines close to 2000 Å, where air absorbs most light. To minimize turbulence and to further reduce the absorption from air the spectrometer was evacuated to a pressure of about 0.015 torr.

To ensure the lines are unaffected by self-absorption the quantity of each metal inserted in the cathode had to be varied and tested through a large number of recorded spectra. This was especially the case for the Zn II doublet. With just a trace of Zn the lines were...
strong but unaffected by self-absorption. For the Mg I lines the procedure was similar, but the strong λ2852 Å line and the much weaker λ2026 Å line had to be measured in different recordings. The weak λ2026 Å line had to be measured with more Mg in the cathode, which gave a clearly self-reversed profile for the strong λ2852 Å line. The λ2852 Å line was therefore measured in the same recording as the Ti II lines. The lamp conditions and spectrometer resolution for the three recordings are listed in Table 1.

To further investigate the effects of possible self-absorption and pressure shifts of the lines, recordings were also made with different currents and pressures in the light source. The effects were considered negligible and are discussed in Sections 3.1, 3.3 and 3.4.

3 ANALYSIS

3.1 Wavenumber calibration

Spectra observed by FT spectrometry have a linear wavenumber scale, whose accuracy derives from the control of the sampling of the interferogram by a single-mode helium–neon laser, whose frequency is stabilized to five parts in 10^9. The accuracy is however limited by the effects of using a finite-size aperture and by imperfect alignment of the light from the light source and the control laser. To obtain a wavenumber scale which is accurate to better than one part in 10^7, a multiplicative correction is applied using a correction factor, \( k_{\text{eff}} \), such that

\[
\sigma_{\text{corr}} = (1 + k_{\text{eff}}) \sigma_{\text{obs}},
\]

where \( \sigma_{\text{corr}} \) is the corrected wavenumber and \( \sigma_{\text{obs}} \) is the observed, uncorrected wavenumber.

The factor \( k_{\text{eff}} \) is accurately determined by measuring positions of one or several well-known internal wavenumber standard lines. In principle, it is possible to use only one calibration line (Salit et al. 2004), but to reduce the uncertainty of the calibration, several calibration lines have been used for each recorded spectrum. The use of internal calibration lines, in this case Ar II lines from the carrier gas in the HCL, helps to ensure, to as high degree as possible, that the light from the species being used for wavelength calibration illuminates the entrance aperture of the FT spectrometer in the same way as that of the species being investigated.

Ar II lines are commonly used for calibrating spectra and there are in principle two sets of standard lines available. The general opinion is now that the work by Whaling et al. (1995) should be used instead of the work by Norlén (1972), which has previously been the standard. The wavenumbers of Whaling are stated to have a correction factor. The error bars in Fig. 2 include both Whaling’s and Norlén’s values.

The calibration lines selected for recording number I are 14 Ar II 4s–4p transitions from Whaling et al. (1995) with signal-to-noise ratios larger than 100. Most of the lines used are transitions recommended by Learner & Thorne (1988) to be least affected by pressure shifts. The pressure shift generally increases with excitation. Because of the few low levels in Ar II this leads to the fact that excitation and thus pressure shift increases with the wavenumber of the lines. The pressure in the cathode used by Whaling et al. (1995) (1–4 torr) differs from the pressure used in this work (0.9–1.0 torr). Using the least pressure sensitive 4s–4p transitions minimizes the possible effects from this pressure difference. Fig. 2 shows a plot of \( k_{\text{eff}} \) versus \( \sigma \) for the 14 Ar II calibration lines in recording number I. The plot deviates slightly from the expected horizontal straight line even with the restricted set of 4s–4p lines. It appears to change by three parts in 10^8 over 5000 cm^{-1} giving rise to an uncertainty in the calibration. The adopted correction factor is derived by taking the weighted mean of the correction factors from the 14 calibration lines, where the weight is scaled with the inverse variance of each correction factor. The error bars in Fig. 2 include both Whaling’s quoted uncertainty and the uncertainty in our line fitting procedure, see Sections 3.2 and 4.1. The dashed line in Fig. 2 marks the adopted correction factor.

In recordings number II and III, covering higher wavenumbers, there are an insufficient number of reliable Ar II calibration lines available in our spectra. Only three 4s–4p transitions have sufficient signal-to-noise ratios (>100) for calibration purposes and these might possibly be affected by pressure shifts due to their higher wavenumbers (see previous discussion). A transfer of

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**Table 1. Lamp conditions, resolution and correction factors.**

| Recording number | Wavenumber range (cm^{-1}) | Cathode | Carrier gas | Pressure (torr) | Current (mA) | Resolution (cm^{-1}) | \( k_{\text{eff}} \) |
|------------------|-----------------------------|---------|-------------|----------------|-------------|-----------------------|-----------------|
| I                | 20538–41074                 | Composite | Ar & Ne    | 0.9            | 700         | 0.05                  | \((-2.12 \pm 0.02) \times 10^{-6}\) |
| II               | 25277–50553                 | Composite | Ar & Ne    | 1.0            | 600         | 0.06                  | \((-2.23 \pm 0.03) \times 10^{-6}\) |
| III              | 26857–53713                 | Pure Fe | Ar         | 1.0            | 700         | 0.04                  | \((-2.54 \pm 0.03) \times 10^{-6}\) |

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**Figure 1.** Comparison between 4s–4p Ar II wavenumbers from Whaling et al. (1995) and Norlén (1972) \( (\Delta \sigma = \sigma_{\text{Whaling}} - \sigma_{\text{Norlén}}) \). The error bars include the quoted uncertainties of both Whaling’s and Norlén’s values.
calibration between the two wavenumber regions was therefore used. In recording number I, which includes the 14 Ar II calibration lines, a number of Fe I and Fe II lines were measured and calibrated. These lines are located in the overlap of the two wavenumber intervals and are observed in all three recordings. They could therefore be used together with three Ar II lines for calibration in recordings number II and III. The uncertainty of the calibration of the higher wavenumbers are slightly larger due to this two-step calibration.

Fig. 3 shows a plot of $k_{\text{eff}}$ versus $\sigma$ for the Fe I, Fe II and Ar II calibration lines used in recording number II. The Fe lines and Ar II lines seem to give the same correction factor implying that the possible pressure shift in the Ar II lines used from Whaling et al. (1995) is negligible.

To investigate the possible shifts of the Ar II lines further another calibration of recording number II was made by including strong 4s–4p, 3d–5p, 4p–4d, 4p–5d and 4p–6s Ar II transitions from Whaling et al. (1995), see Fig. 4. The resulting correction factor differs no more than one part in 10^8 from the value derived from the Fe calibration lines in the overlap region, which is well within the estimated uncertainty.

The HCL is only stable within a small pressure range, but to investigate possible effects of pressure shifts measurements were made with three different pressures (0.8, 1.0 and 1.2 torr) in the light source, keeping the rest of the parameters (i.e. the current and the quantity of metal in the HCL, and the spectrometer settings) constant. The possible effects of shifting wavenumbers and varying calibration factors, for this small pressure range, were well within the uncertainties.

3.2 Line fitting

All lines except the Mn lines show no structure and consist of an apparently symmetric peak profile, see Fig. 5 where the observed profiles of the Mg, Ti, Cr, Fe and Zn lines are plotted. Possible unresolved isotope shifts are discussed in Section 3.4. The symmetric lines were fitted with Voigt profiles using a least-square procedure included in the FT spectrometry analysis program xGREMLIN (Nave, Sansonetti & Griesmann 1997), which is based on the GREMLIN code (Brault & Abrams 1989).

3.3 Mn hyperfine structure

The manganese lines consist of several peaks arising from the hyperfine structure. Mn consists of only one natural isotope, ${}^{55}\text{Mn}$, which has a nuclear spin of $I = 5/2$ and a magnetic dipole moment of 3.45. This gives rise to a large hyperfine structure in the lines. The structure is however only partially resolved, see Fig. 6. The structure of Mn II resonance lines is previously reported (Kling & Griesmann 2000), but the hyperfine constants for the energy levels included in the present investigation have not been measured until recently (Blackwell-Whitehead et al. 2005).

Since the structure of the Mn II lines is unresolved the wavenumbers were determined by measuring the Centre-of-Gravity (CoG) wavenumbers of the lines instead of fitting a Voigt profile as for the other lines. The CoG of a line was determined by choosing a start and an end point symmetrically located at each side of the line profile. The area and the CoG were then calculated for the region between the two points. This was done 20 times for each line, over regions with varying widths, and a mean was adopted as the wavenumber of the line. Because of the strength of the lines this gave a consistent result with an estimated uncertainty small enough to
match the required precision for MM analysis, see Sections 4.1 and 1.

The effect of a possible self-absorption of the Mn II lines could be that the observed CoG is shifted towards the weaker hyperfine components. To test this recordings were made with different currents through the HCL. This would lead to different plasma densities in the cathode and thus different amount of self-absorption. The lower the current, the lower the density and self-absorption. Fig. 7 shows...
Accurate laboratory UV wavelengths

3.4 Possible isotope structure

Although the lines from Mg, Ti, Cr, Fe and Zn appear to be symmetric and the residuals from the line fitting showed no asymmetry, a further investigation of possible unresolved isotope structure was carried out. For Cr and Fe any isotope or hyperfine structure should be negligible compared to the Doppler width and they both have one dominating isotope (52Cr: 84 per cent and 56Fe: 92 per cent). Since the Fe II lines are of great importance to the MM method, the observed line profiles were compared to synthetic profiles consisting of components from the most abundant isotopes (54Fe: 6 per cent, 56Fe: 92 per cent and 57Fe: 2 per cent). Transition shifts larger than ~ 0.06 cm⁻¹, between the 54Fe and 56Fe isotopes, violated the observed profile and the shifts should therefore be smaller than that.

Both Ti and Mg consist of one even isotope each with a large relative abundance and a couple of other isotopes with relative abundances between 5 and 10 per cent. The lines measured showed no form of self-absorption, which could have been a problem since unresolved structure might cause a small shift in the wavenumbers of the lines had they been affected by self-absorption. A thorough investigation of the isotope structure of the Mg I λ2796 Å and Mg II λλ2796,2803 Å lines has been made by Pickering et al. (1998).

The Zn II doublet was investigated more thoroughly since Zn has three main isotopes (64Zn: 49 per cent, 66Zn: 28 per cent and 68Zn: 19 per cent) and the lines showed clearly self-absorbed profiles during the test runs. To ensure that the possible self-absorption did not shift the lines the discharge current was varied between 0.3 and 0.7 A. This would produce different plasma densities and thus different amount of self-absorption. In Fig. 8, the differences in the fitted

Figure 6. The observed profiles of the Mn II lines in this study, showing unresolved hyperfine structure. The lines are centred in a wavenumber interval of ±1.0 cm⁻¹.

Figure 7. Test for optical thickness for the Mn II lines. The error bars represent the relative uncertainty of the CoG for the Mn II lines, not including the uncertainty of the calibration lines.

Figure 8. Test for optical thickness for the Zn II lines. The error bars represent the relative uncertainty of the wavenumber for the Zn II lines, not including the uncertainty of the calibration lines.
wavenumbers of the Zn II lines are plotted at different discharge currents. Similar to the Mn II lines, no shift or tendency is apparent. The transition isotope shifts for the Zn II λ2026 Å line have been measured, using laser technique, by Matsubara et al. (2003) reporting shifts of 0.670–0.676 GHz (corresponding to 0.022–0.023 cm$^{-1}$) for the mentioned isotopes. This is small compared to the Doppler wavenumbers compared to the Whaling et al. (1995) wavenumbers from Norlén (1972). There is a systematic difference between these spectrometry measurements of the Cr II, Zn II (Pickering et al. 2000), Mg II lines and the Mg I λ2852 Å line (Pickering et al. 1998) have been made for the same reason as this investigation (these are included in Morton 2003). Pickering et al. (2000) measured the lines at two different laboratories [Imperial College, London (ICL), and Lund (LU)] to ensure a minimization of systematic errors. At LU a composite cathode was used, similar to the present investigation, to reduce the relative uncertainties. The published values for Cr and Zn were, however, weighted means of the ICL and LU results.

One significant difference between the previous LU–ICL and the present investigations is the calibration. The previous wavenumbers have been calibrated directly or indirectly with Ar II lines from Nave et al. (1991). Also these wavenumbers were calibrated with Ar II lines from Norlén (1972) and should therefore be lower, by 0.003 cm$^{-1}$, than the wavenumbers measured in this investigation. The estimated uncertainties are however larger than for symmetric lines, both for our measurements and for those of Blackwell-Whitehead, due to the hyperfine structure. The measurements agree, within the uncertainties, when the calibration difference is taken into account.

The previous values for Ti II are unpublished FT spectrometry measurements by Zapadlik et al. (private communication, published in Morton 2003), also calibrated with Ar II lines from Norlén (1972), while the Mg I λ2026 Å and Fe II λ2260 Å lines are measured using grating technique and have much lower precision and calibration accuracy.

4 RESULTS

The measured wavenumbers, wavelengths and uncertainties of the 23 lines are presented in Table 2. The wavenumbers are compared to previously published values.

For the MM method it is the relative shifts of the lines that is most important. The present investigation therefore includes lines from different species measured in the same recordings, which reduces the uncertainties of the relative wavenumbers. Previous FT spectrometry measurements of the Cr II, Zn II (Pickering et al. 2000), Mg II lines and the Mg I λ2852 Å line (Pickering et al. 1998) have been made for the same reason as this investigation (these are included in Morton 2003). Pickering et al. (2000) measured the lines at two different laboratories [Imperial College, London (ICL), and Lund (LU)] to ensure a minimization of systematic errors. At LU a composite cathode was used, similar to the present investigation, to reduce the relative uncertainties. The published values for Cr and Zn were, however, weighted means of the ICL and LU results.

Table 2. Wavelengths, wavenumbers and comparison to previous values. $\lambda_{\text{MM}}$ is derived by the Edlén (1966) dispersion formula for air at 15°C and atmospheric pressure.

| Species | $\lambda_{\text{MM}}$ (Å) | $\lambda_{\text{MM}}$ (Å) | Wavenumber (cm$^{-1}$) | Recording number | Previous value (cm$^{-1}$) | Reference |
|---------|----------------|----------------|----------------|-----------------|----------------|-----------|
| Mg I    | 2852.1248      | 2852.9628 ± 0.0001 | 3505.280 ± 0.002 | I               | 3505.277 ± 0.001 | Pickering et al. (1998) |
| Mg II   | 2052.8224      | 2052.6750 ± 0.0003 | 4934.771 ± 0.003 | II              | 4934.729 ± 0.070 | Risberg (1965) |
| Mg II   | 2802.7052      | 2803.5311 ± 0.0005 | 3569.303 ± 0.002 | II              | 3569.298 ± 0.002 | Pickering et al. (1998) |
| Mg II   | 2795.5299      | 2796.3540 ± 0.0001 | 3576.851 ± 0.002 | II              | 3576.848 ± 0.002 | Pickering et al. (1998) |
| Ti II   | 3383.7584      | 3384.7300 ± 0.0002 | 2954.454 ± 0.001 | I               | 2954.451 ± 0.003 | Zapadlik et al. (private communication) |
| Ti II   | 3241.9825      | 3242.9180 ± 0.0002 | 3083.426 ± 0.001 | I               | 3083.422 ± 0.003 | Zapadlik et al. (private communication) |
| Ti II   | 3229.1895      | 3230.1217 ± 0.0001 | 3095.858 ± 0.001 | I               | 3095.858 ± 0.002 | Zapadlik et al. (private communication) |
| Ti II   | 3072.9701      | 3073.8629 ± 0.0001 | 3252.335 ± 0.001 | I               | 3252.335 ± 0.003 | Zapadlik et al. (private communication) |
| Ti II   | 3066.3466      | 3067.2375 ± 0.0002 | 3260.627 ± 0.002 | I               | 3260.623 ± 0.003 | Zapadlik et al. (private communication) |
| Cr II   | 2065.5039      | 2065.1639 ± 0.0001 | 4839.871 ± 0.002 | II              | 4839.868 ± 0.002 | Pickering et al. (2000) |
| Cr II   | 2061.5676      | 2062.2359 ± 0.0001 | 4849.057 ± 0.002 | II              | 4849.053 ± 0.002 | Pickering et al. (2000) |
| Cr II   | 2055.5987      | 2056.2568 ± 0.0001 | 4863.058 ± 0.002 | II              | 4863.055 ± 0.002 | Pickering et al. (2000) |
| Mn II   | 2605.6804      | 2606.4588 ± 0.0002 | 3836.230 ± 0.003 | II              | 3836.227 ± 0.003 | Blackwell-Whitehead et al. (2005) |
| Mn II   | 2593.7211      | 2594.4967 ± 0.0002 | 3854.123 ± 0.003 | II              | 3854.122 ± 0.003 | Blackwell-Whitehead et al. (2005) |
| Mn II   | 2576.1039      | 2576.8753 ± 0.0002 | 3880.689 ± 0.003 | II              | 3880.689 ± 0.003 | Blackwell-Whitehead et al. (2005) |
| Fe II   | 2599.3953      | 2600.1722 ± 0.0001 | 3845.991 ± 0.002 | II              | 3845.987 ± 0.002 | Nave et al. (1991) |
| Fe II   | 2585.8756      | 2586.6694 ± 0.0001 | 3866.052 ± 0.002 | III             | 3866.049 ± 0.002 | Nave et al. (1991) |
| Fe II   | 2382.0375      | 2382.7641 ± 0.0001 | 4196.065 ± 0.002 | II              | 4196.064 ± 0.002 | Nave et al. (1991) |
| Fe II   | 2373.7354      | 2374.4601 ± 0.0001 | 4211.836 ± 0.002 | II              | 4211.833 ± 0.002 | Nave et al. (1991) |
| Fe II   | 2343.4949      | 2344.2128 ± 0.0001 | 4265.243 ± 0.002 | II              | 4265.240 ± 0.002 | Nave et al. (1991) |
| Fe II   | 2260.0797      | 2260.7793 ± 0.0003 | 4423.534 ± 0.006 | II              | 4423.512 ± 0.020 | Johansson (1978) |
| Zn II   | 2062.0010      | 2062.6603 ± 0.0001 | 4848.081 ± 0.002 | II              | 4848.077 ± 0.002 | Pickering et al. (2000) |
| Zn II   | 2025.4844      | 2026.1369 ± 0.0001 | 4935.005 ± 0.002 | II              | 4935.002 ± 0.002 | Pickering et al. (2000) |

$^a$Published in Morton (2003).
4.1 Uncertainties

The absolute wavenumber uncertainty contains two main factors: the uncertainty of the calibration and the uncertainty of the determination of the line position. The standard deviation \( s(\sigma) \) of the line position \( \sigma \) of a fitted line profile can be written as (Brault 1987; Sikström et al. 2002)

\[
s(\sigma) = \alpha_\sigma \sqrt{\frac{d\ell}{S}} \sqrt{w} = \alpha_\sigma \frac{w}{S\sqrt{n}},
\]

where \( S \) is the signal-to-noise ratio for the line, \( dx \) is the resolution interval and \( w \) is the full width at half-maximum (FWHM) of the line. The number of points across the width of the line is given by \( n = w/dx \). \( \alpha_\sigma \) is a numerical constant depending on the shape of the line. For a pure Gaussian profile the value is \( \alpha_{\sigma,G} = 0.69 \pm 0.02 \) and for a pure Lorentzian profile the value is \( \alpha_{\sigma,L} = 0.80 \pm 0.13 \) (Sikström et al. 2002).

The uncertainty from the calibration is derived from the uncertainties stated by Whaling et al. (1995), from the uncertainties of the line positions of the calibration lines and from the standard deviation of the calibration factors.

For the Mn II lines the CoG is given and the uncertainty is estimated by calculating the standard deviation of 20 different measurements of the CoG (in one recording) of each line, adding the standard deviation given by making the same measurements in different recordings (with different lamp conditions) and finally including the uncertainty of the calibration. This resulted in a total uncertainty of \( \pm 0.003 \) \( \text{cm}^{-1} \) for the three Mn II lines.

The difference in wavenumbers between two lines measured in the same recording follows from equation (1) and can be expressed as

\[
\sigma_1 - \sigma_2 = (1 + k_{\text{eff}})(\sigma_{\text{obs,1}} - \sigma_{\text{obs,2}}),
\]

where \( k_{\text{eff}} \) is the calibration factor for the recorded spectrum. By applying the law of propagation of uncertainty, the expression for the uncertainty of the difference in wavenumber becomes

\[
s(\sigma_1 - \sigma_2) = \left\{ (1 + k_{\text{eff}})^2 [s(\sigma_{\text{obs,1}})^2 + s(\sigma_{\text{obs,2}})^2] + (\sigma_{\text{obs,1}} - \sigma_{\text{obs,2}})^2 s(k_{\text{eff}})^2 \right\}^{1/2},
\]

where \( s(\sigma_{\text{obs,1}}) \) is the uncertainty of the determination of the line position for line \( i \), see equation (2), and \( s(k_{\text{eff}}) \) is the uncertainty of the calibration factor for the observed spectrum, see Table 1. This means that for symmetric lines with high signal-to-noise ratios (>250) the relative wavenumbers (for lines within the same spectral recording) are determined with an uncertainty of \( \pm 0.0005 \) \( \text{cm}^{-1} \), or better. The uncertainty is smallest for lines which are close in wavenumber, due to the linear correction, and then depends mostly on the line fitting.

5 CONCLUSIONS

Constraints on possible cosmological variations in the fine-structure constant rely crucially on comparison with accurate laboratory standards. Here we have measured 23 transitions, with particular emphasis on relative wavelength precision, which are central to MM analyses of QSO absorption spectra. The precision is improved by measuring the lines simultaneously from a composite light source. The lines are calibrated against new secondary standard lines of Ar II, produced in the same light source. The estimated absolute uncertainty is 0.1 mÅ for 15 lines, 0.2 mÅ for seven lines and 0.3 mÅ for one line. It should be pointed out that the Mn II lines are severely broadened due to unresolved hyperfine structure, and that their wavelengths represent CoG values. The relative wavenumbers for strong, symmetric lines in the same spectral recording are determined with an uncertainty of 0.03 mÅ at 2500 Å.

This is the first time the five transitions of Ti II and the Mg I \( \lambda \)2026 and Fe II \( \lambda \)2260 transitions have been measured with sufficient precision for use in the MM method. The remaining 16 transitions of Mg I, Mg II, Cr II, Mn II, Fe II and Zn II have been measured to as high precision before using a different set of calibration lines. The importance of repeated laboratory measurements cannot be emphasized enough given the role they play in fundamental physics experiments at cosmological distances and look-back times.

Because of the newly adopted wavenumbers for a set of Ar II calibration lines the absolute wavenumbers of the majority of the lines have been shifted by about 0.003 \( \text{cm}^{-1} \) (about 0.1–0.2 mÅ) compared to previous values (see e.g. Morton 2003). The wavelengths which have been measured to as high a precision before agree with the present wavelengths to within the uncertainties, when this calibration difference is taken into account. This leads to a greater confidence in these wavelengths, while the high relative precision in this work reduces the potential for systematic effects in the MM method. As all 23 lines measured are ground state transitions they also usually appear as sharp interstellar lines in stellar spectra.

ACKNOWLEDGMENTS

We are grateful to Dr U. Litzén for valuable comments on the manuscript. This project is supported by a grant (SJ) from the Swedish Research Council. MTM thanks PPARC for an Advanced Fellowship.

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